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Development and Application of a Risk Assessment Method for Radioactive Waste Management
Volume I: Generic Description of AMRAW-A Model

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Development and Application of a Risk Assessment Method for Radioactive Waste Management

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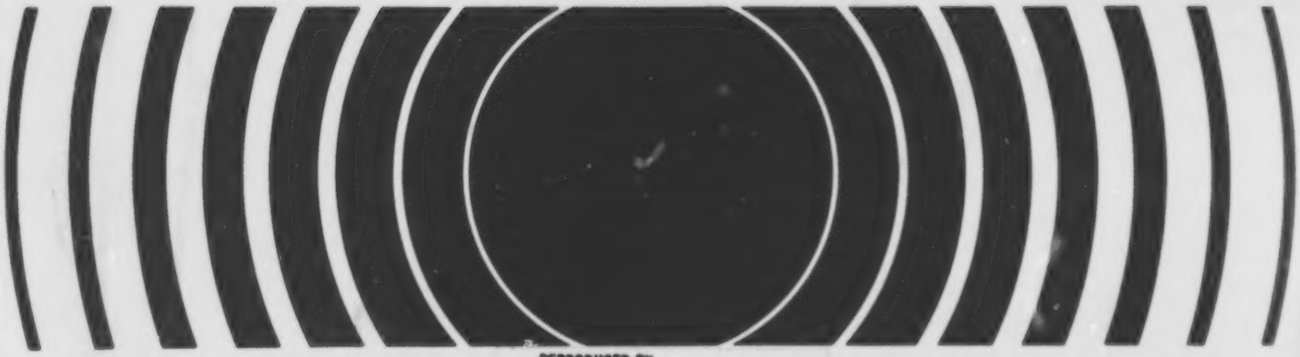

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16. ABSTRACT

A Radioactive Waste Management Systems Model, developed and implemented by The University of New Mexico under contract with the U.S. EPA, is presented. The systems model and associated computer code called AMRAW (Assessment Method for Radioactive Waste), has two parts. The first part, AMRAW-A, consists of the Source Term (radioactive inventory versus time), the Release Model, and the Environmental Model. The Release Model considers various geologic and man-caused events which are potential mechanisms for release of radioactive material from a repository or other location of emplacement. The environmental model describes the transport to and accumulation at various receptors in the biosphere, the transfer to man via various pathways, and the resulting radiation does. The systems model can be run in either of two modes determined by the manner in which postulated release events are assumed to occur. Release events can either be treated as discrete events occurring at specified times, or as probabilistic events distributed over time. The second part of the systems model, AMRAW-B, the Economic Model calculates health effects corresponding to the various organ dose rates from AMRAW-A, collects these health effects in terms of economic costs and attributes these costs to radionuclides, decay groups, and elements initially in the waste inventory. The implementation of AMRAW for terminal storage in a bedded salt reference repository is described and the application to a reference repository in a shale formation is discussed. Application to the repository operations phase and to the analysis of disposal of nonradioactive hazardous materials is also discussed.

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DEVELOPMENT AND APPLICATION OF A RISK ASSESSMENT METHOD FOR RADIOACTIVE WASTE MANAGEMENT

Final Contract Report
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Bureau of Engineering Research
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Volume I: Generic Description of AMRAW-A Model

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July 1978

Prepared for
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FOREWORD

The EPA Office of Radiation Programs carries out a national program to evaluate human exposures to radioactivity, and to promote the development of controls to protect the environment and public health from such radioactivity. An important part of this program consists of the development of environmental protection criteria and standards for radioactive waste management and disposal.

To sustain this effort, studies have been supported by EPA to develop methods to evaluate the environmental adequacy of proposed waste management alternatives, and this report describes one of the first attempts to develop a comprehensive assessment model. It has been funded at a very modest level. Much interest has been expressed in this work, and through publication, EPA is making it available to those involved with the development and use of models as decision-making tools.

In order for models to be useful as tools for decision-making concerning radioactive waste management alternatives, their capabilities and limitations must be fully understood. It should be noted that assessment models in themselves will not identify optimum waste management choices. However, they can be used to compare well defined alternatives. One of the necessary steps in any model development and validation process is the comparison of results with results obtained from the application of alternate models to test cases. It is hoped that as other comprehensive assessment models become available, comparison studies can be performed.

The methodology described herein has been applied, for model illustration purposes, to a reference repository in a bedded salt formation located in the southwestern United States. Any results published in this report should not be interpreted as implying conclusions concerning the suitability of the reference site or any site-specific method/repository combination for the preparation and disposal of radioactive waste.

Comments on this analysis as well as any new information would be welcomed; they may be sent to the Director, Technology Assessment Division (AW-459) Office of Radiation Programs, U.S. Environmental Protection Agency, Washington, D.C. 20460.

W. D. Rowe, Ph.D.
Deputy Assistant Administrator
for Radiation Programs (AW-459)

ABSTRACT

A Radioactive Waste Management Systems Model, developed and implemented by The University of New Mexico under contract with the U. S. Environmental Protection Agency, is presented. The systems model and associated computer code called AMRAW (Assessment Method for Radioactive Waste), has two parts. The first part, AMRAW-A, consists of the Source Term (radioactive inventory versus time), the Release Model, and the Environmental Model. The Release Model considers various geologic and man-caused events which are potential mechanisms for release of radioactive material beyond the immediate environs of a repository or other location; the risk analysis mode uses events distributed probabilistically over time, and the consequence analysis mode uses discrete events occurring at specified times. The Environmental Model includes: 1) the transport to and accumulations at various receptors in the biosphere, 2) pathways from these environmental concentrations, and 3) resulting radiation dose to man.

The second part of the systems model, AMRAW-B, is the Economic Model which calculates health effects corresponding to the various organ dose rates from AMRAW-A, collects these health effects in terms of economic costs and attributes these costs to radionuclides, decay groups, and elements initially in the waste inventory. Implementation, with calculated results, of AMRAW for Terminal Storage in a Bedded Salt Reference Repository are presented. Preliminary demonstrations for the repository operations phase of waste management and terminal storage in a shale formation are described; possible applications to other radioactive and nonradioactive hazardous materials are discussed. AMRAW uniquely links all steps together in a continuous calculation sequence.

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The work on this broad interdisciplinary program centered in the Chemical and Nuclear Engineering Department (Ch/NE) of the College of Engineering at The University of New Mexico (UNM). The principal investigator, S. E. Logan, was assisted by M. C. Berbano and numerous graduate students in Ch/NE. A component of the effort concerned the Economic Model, handled by the UNM Economics Department. Other departments at UNM provided support in areas of geologic descriptions and disruptive events, environmental pathway analysis, and computer programming. UNM departments and personnel participating at various levels of activity and at various times during the study are as follows:

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Other persons outside of UNM contributed significantly to the completion of the study through their direct participation, the furnishing of categories of data, or helping with critical reviews of draft versions of the report. These individuals are listed below under AMRAW sub-models. It should be noted that participation by these persons does not necessarily imply their endorsement of the AMRAW methodology or any of its components.

Inventory at Risk (Source Term). J. O. Blomeke of ORNL (Oak Ridge National Laboratory) furnished ORIGEN computer output for radioactive waste projections.

Release Model. A. Sanford (New Mexico Institute of Mining & Technology) conducted a seismic analysis for the model repository site; I. J. Winograd (U.S. Geological Survey) and H. Lambert (consultant) provided critical reviews.

Transport to Environment. T. E. Kelly (Geohydrology Associates) provided hydrologic study for the model repository site; J. O. Duguid (ORNL, now at Battelle Columbus Laboratories) provided a description of the Duguid-Reeves ground water transport model; R. E. Moore (ORNL) provided air dispersion computer output from the AIRDOS code; T. H. Pigford (University of California) and H. C. Burkholder (Battelle Pacific Northwest Laboratories) provided critical review of ground water transport.

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DEVELOPMENT AND APPLICATION OF A RISK ASSESSMENT METHOD FOR RADIOACTIVE WASTE MANAGEMENT

VOLUME LISTING

VOLUME I	GENERIC DESCRIPTION OF AMRAW-A MODEL
VOLUME II	IMPLEMENTATION FOR TERMINAL STORAGE IN REFERENCE REPOSITORY AND OTHER APPLICATIONS
VOLUME III	ECONOMIC ANALYSIS; DESCRIPTION AND IMPLEMENTATION OF AMRAW-B MODEL
VOLUME IV	AMRAW COMPUTER CODE USERS' MANUAL

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LIST OF ABBREVIATIONS, SYMBOLS AND NOMENCLATURE

CHAPTER 1

None

CHAPTER 2

AMRAW	(Assessment Method for Radioactive Waste) Assessment Model and associated computer code
AMRAW-A	That portion of AMRAW which includes Source Terms, Release Model, and Environmental Model
AMRAW-B	The economic part of AMRAW
K_d	Distribution coefficient used in ground water transport calculations

CHAPTER 3

None

CHAPTER 4

Section 4.A

None

Section 4.B

e_{th}	Thermal efficiency
E_{th}	Thermal energy produced
F	Capacity factor
P_e	Rated electrical power capacity
t	Duration of time period

Section 4.C.1

A_1, A_2	Fault tree "and" gates
Al(t)	Fraction of inventory transferred to a given input receptor if release occurs
A(t)	Transfer coefficient to given preliminary environmental input receptor
B_1, B_2	Fault tree "or" gates
B & C	Constants used in illustrating forms of P(t)

P(t)	Annual probability of release occurrence
t_p	Time at which P(t) commences change or when discrete event occurs in using delta function
Δt	Time increment within which t_p lies in using delta function.
X_1, X_2, etc.	Probability factors
Section 4.C.2.	None
Section 4.C.3.	
a_n	Incremental amount leached for n leach period renewals
A_o	Initial total radioactivity of species subject to leaching
C	Concentration of mobile species at time t and space x
C_s	Uniform initial concentration of mobile species
$\mathcal{D}_e$	Effective diffusivity for the species
F_s	Total exposed area of specimen
J(t)	Radioactive species material flux across interface
k	Dissolution rate constant
K	Stokes-Einstein constant, 1.38×10^{-16} g cm^2/sec^2 molecules °K
L	Cumulative amount of radioactive isotope leached from solidified waste for a specified
L_p	$\sum_m a_n$
M	Molecular weight of diffusing species
M_s	Molecular weight of solvent
N_A	Avogadro's number
R_K	Radius of diffusing particle in cm
t	Time
T	Absolute temperature, °K
V	Molecular volume of the solute at normal boiling point, cm^2/g mole

V_s	Specimen volume
x	Spatial coordinate in cartesian space
y	Spatial coordinate in cartesian space
z	Spatial coordinate in cartesian space
α,β	Empirical constants in leach equation
$\eta(x, t)$	Transformation variable used is solution of diffusion equation
μ	Solvent viscosity at absolute temperature, T °K
ξ	Fraction of initial amount leached
ρ	Density of diffusing species in solid state
χ	An association parameter for the solvent
Section 4.C.4	None
Section 4.D.1	
a'	Modified coefficient of compressibility of the medium
a_L	Longitudinal dispersivity
a_T	Transverse dispersivity
A2	Time transfer coefficient, incorporating radioactive and environmental decay, and transport retardation
AREAG	Zone land surface area
AREAW	Zone surface water area
c	Concentration of the dissolved species
C	Concentration of the dissolved species appearing as the solution to the radionuclide mass transfer equation
$\tilde{D}$	Dispersion tensor
D_{ij}	Component of dispersion tensor $\tilde{D}$
DECFAC	(in AMRAW) Effective decay factor between two times
DEP	Deposition concentration for land and ground surface (Ci/cm^2) due to air deposition

DEPGND	Deposition on land surface of zone
DEPWTR	Deposition on water surface of zone
DISPN	(in AMRAW) Dispersion parameter (land surface area or water volume)
E_m	(ADJ1 in AMRAW) Maximum fraction of inventory (or value of G_m) which can be transferred
E_x	Component along x axis of coefficient of dispersion divided by retardation factor, R_d
E_y	Component along y axis of coefficient of dispersion divided by retardation factor, R_d
f_m	Fraction of amount of species sorbed on solid medium per unit mass of medium
f_s	Fraction of amount of species remaining in solution per unit volume of solution
F_m	(ADJ2 in AMRAW) Transfer rate constant
F_o	Storage constant
g	Gravitational constant
G_m	(ADJ in AMRAW) Fraction of inventory transferred from one receptor pool to another pool per unit time
GNDEP	(in AMRAW) Non-accumulating matrix which retains integrated deposition for current time increment for use in calculating transfer to terrestrial food products
h	Pressure head
H	Total hydraulic head
$\bar{\bar{k}}$	Intrinsic permeability tensor
$\bar{\bar{K}}$	Hydraulic conductivity tensor
K	Scalar limit of $\bar{\bar{K}}$ for homogeneous and isotropic medium
K_d	Distribution coefficient--a measure of retention of species on porous medium
M	Amount of particular radionuclide released by leaching during a release time interval, Ci
M'	Ratio of amount leached, M, to the thickness of aquifer in which leached, Ci/m

P_o	Pressure at arbitrary datum z_o
P_1	Pressure at elevation z_1
R_d	Retardation factor
R1J	Release increment to Preliminary Input Receptor
R2	Environment Input Receptor inventory by zone
R2CON	(in AMRAW) Concentration components
R2TOT	(in AMRAW) Accumulated net total concentration in µCi per cm^2 or cm^3 by zone and Environmental Input Receptor
Δt	(DELTE in AMRAW) Time interval over which environmental decay constant is applied; also, time increment for which transfer is calculated
T_o	Transmissivity
U	Pulse velocity
$\|v\|$	Magnitude of Darcy flux
v_i & v_j	Components of the Darcy flux
v_{fs}	Velocity of fluid relative to solid
v_p	Pore (or seepage) velocity
v_s	Velocity of solid
v_x	Fluid velocity in the predominant flow direction ($= \varepsilon \cdot v_p$)
x	Coordinate axis and distance in predominant flow direction
X_{time}	Repository inventory for a particular nuclide at time--input to AMRAW
y	Transverse distance from plume centerline
y_w	Effective width of plume
y_y	Transverse distance corresponding to average concentration
z	Elevation head
z_a	Aquifer thickness
ZONALO	Dispersion allocation factor for air concentration
ZONDEP	Dispersion allocation factor for ground deposition

α	Coefficient of consolidation of the medium
β'	Fluid compressibility
δ_{ij}	Kronecker delta
ε	Porosity
θ	Volumetric moisture content
λ	Radioactive decay constant
λ_e	Environmental decay constant--input to AMRAW
λ_s & η_s	Lame' constants
μ_f	Fluid viscosity
ξ	Macroscopic strain tensor
ρ	Bulk density of porous medium
ρ_f	Fluid density
ρ_f^o	Fluid density at pressure p_o
σ	Incremental pressure in fluid
τ	Dilatation of medium
$\emptyset$	Saturation of porous media: volume fraction of porosity which is water-filled

Section 4.D.2

BIOFAC	Concentration or dilution to the consumed or exposed quantity
C	Transfer coefficient which transforms environmental concentration in a receptor to corresponding dose commitment rate to a specified organ.
CRATIO	Subroutine in AMRAW-A for ground water transport calculations
DELTE	Same as t in Section 4.D.1 time increment for which transfer is calculated
DOSFAC	Dose rate conversion per unit of exposure or consumption for the specified organ
FAULT	Subroutine in AMRAW-A which handles the Release Model and provides transfer coefficients used to accumulate releases to four preliminary input receptors

GNDEP	Same as defined in 4.D.1.
RLEACH	Subprogram in FAULT which handles leaching into ground water
R2TOT	Same as defined in 4.D.1.
TRINP	Subroutine provides transfer coefficients for transport from preliminary input receptors to the environmental input receptors
TRMAN	Subroutine which evaluates transfer coefficients between environmental concentrations and population dose rates for various pathways
VOLINT	Amount of exposure or consumption per year

Section 4.E.

$A1_{ij}(t)$	Transfer coefficient for transfer from repository to receptor j by release mechanism i.
$\left\langle A1_j(t) \right\rangle$	Expectation value for the transfer coefficient from all release events at time t to receptor j
$A2_j(t, T, \vec{r})$	Time transfer coefficient accounting for radioactive and environmental decay between release time t and population dose time T; can account for transport processes in receptor j
$A31(\vec{r})$	Local dose transfer coefficient
$A32(\vec{r})$	Nonspecific transfer coefficient
$DC(t, T)$	Radiodecay factor between times t (release time) and T (population dose time)
$DS(\vec{r})$	Local dispersion factor which provides uniform concentration values of a radionuclide deposited in a zone
$E_m(\vec{r})$	Same as defined in Section D.1.
$F_m(\vec{r})$	" "
$G_m(t, T, \vec{r})$	" "
$H(t, T, \vec{r})$	Total transfer term to receptor j from other receptors m
i	Subscript denoting a release event
j	Environmental receptor of current interest
k	In subscript refers to geographical zone

$L_j(t, T, \vec{r})$	Transfer term representing losses from receptor j to other receptors m
m	Environmental receptor other than j
$M1(T, \vec{r})$	Local man dose rate
$M2(T)$	Nonspecific man dose rate
$P_{ij}(t)$	Probability of release by mechanism i to environmental receptor j during t - dt to t
$q(t, \vec{r})$	Activity in Ci at $\vec{r}$ from nuclide released at time t
$\vec{r}$	Space variable in rectangular coordinates $(\bar{x}, \bar{y}, \bar{z})$
$R(t, T, \vec{r})$	Activity in Ci/cm^2 or Ci/cm^3 at time T at $\vec{r}$ due to release in interval t - dt to t
$RT(T, \vec{r})$	Total activity for all release times-- $\sum_t R(t, T, \vec{r})$
$S(t, T, \vec{r})$	Net total source term representing total activity at $\vec{r}$ in receptor j at time T due to release in interval t - dt to t
t	Release time of radionuclide from waste site to Preliminary Environmental Receptor
$t_{1/2}$	Radioactive half-life
T	Time of interest for population doses
$X(o)$	Amount of nuclide at some reference time
$X(t)$	Amount of nuclide at time of release
$Y(t)$	Radioactivity in Ci at time t for radionuclide of interest
$Z(\vec{r})$	Fraction of released nuclide deposited at position $\vec{r}$
α	In superscript to refer to release time
β	In superscript to refer to population dose time
δ	$(= \int d\tau)$ Period during which transfer calculation of G_m is calculated
λ	Radioactive decay constant
τ	Variable, time
ω_o	Specific activity in Ci/g of a particular nuclide of interest

Appendix A

f	Width of rectangular plane source
M''	Ratio of amount leached during a release time interval per unit area of a plane source, Ci/m^2
Others:	See Section 4.D.1

Appendix B

A	Soil surface area required to furnish food crops for one man ($10^3 m^2$)
B	Concentration of radioactivity in beef ($\mu Ci/kg$)
BIOFAC	Same as defined in Section 3.D.2.
C	Concentration of radioactivity in the milk ($\mu Ci/\ell$)
d_1, d_2, d_3, d_4	Dietary factors that correct the transfer coefficients to man from those for "reference man" to those for the population under study (dimensionless)
D	Radioactivity present in the soil below the root depth ($\mu Ci/m^2$)
E	Radioactivity present on the above-surface food per m^2 of surface on which the food crop is grown ($\mu Ci/m^2$)
F	Fallout source, which for this calculation was assumed to be present only at time $t = 0$ ($\mu Ci/m^2$-d)
F_o	Ground deposition source ($\mu Ci/m^2$)
G	Radioactivity present in the grass compartment ($\mu Ci/m^2$)
M	Radioactive present in man (μCi)
P	Radioactivity present in the subsurface pool associated with one man's food supply (μCi)
R	Radioactivity present in the soil from the ground surface to the root depth of the grass ($\mu Ci/m^2$)
S	Radioactivity present at the soil surface ($\mu Ci/m^2$)
S_1, S_2, S_3	Fallout correction factor to account for different depositions to the above-surface food (S_1), the soil below this food (S_2), and the pasture (S_3) (dimensionless)
δ	Kronecker delta function

λ_e	Turnover rate of the stable isotope of the nuclide in man (d^{-1}) except for Sr where λ_e was isotope-dependent
λ_r	Radioactive decay rate of the nuclide under study (d^{-1})
τ_{beef}	Fraction of the beef herd slaughtered per day (0.00381 d^{-1})
τ_{milk}	Transfer rate of milk from the udder (2.0^{-1})
$\tau_{b,m}$	Amount of meat eaten by a man each day (0.3 kg/d)
$\tau_{c,m}$	Amount of milk consumed by a man each day (1.0 ℓ/d)
$\tau_{e,m}$	Crop harvest rate, m^2/d
$\tau_{e,s}$	Fractional transfer rate, crops to soil surface (0.0495 d^{-1})
$\tau_{g,b}$	Transfer rate, grass to meat, $m^2/kg\text{-}d$
$\tau_{g,c}$	Transfer rate, grass to milk, $m^2/\ell\text{-}d$
$\tau_{g,r}$	Fractional transfer rate, grass to soil, 0.0495 d^{-1}
$\tau_{p,d}$	Fractional transfer rate, soil pool to soil sink, 1.096×10^{-4} d^{-1}
$\tau_{p,m}$	Fractional transfer rate, soil pool to man, d^{-1}
$\tau_{r,d}$	Fractional transfer rate, pasture soil to soil sink, 1.096×10^{-4} d^{-1}
$\tau_{r,g}$	Fractional root uptake rate, soil to grass, 2.74×10^{-5} d^{-1}
$\tau_{s,p}$	Fractional transfer rate, soil surface to soil pool, 0.0693, 0.00693, and 0.000693 d^{-1} (each problem run three times once for each value of $\tau_{s,p}$ listed)

CHAPTER 1

INTRODUCTION

One of the major environmental concerns associated with the projected increase in nuclear power generation is the handling and disposal of high-level radioactive waste. During operation of a nuclear reactor, fissioning fuel atoms result in an accumulation of fission products within each fuel element of the reactor core. These fission products are isotopes of lighter elements and many of these isotopes are radioactive. Significant examples are Sr-90, Tc-99, I-129, Cs-135, and Cs-137. In addition, isotopes of actinide elements, primarily neptunium, plutonium, americium and curium, are created because of neutron absoptions which do not result in fission. Approximately one-third of the energy-releasing fissions in a light water reactor (LWR) are of plutonium which is created during reactor operation. Periodically, because of depletion of fuel atoms and accumulation of neutron-absorbing fission products, a portion of the core must be removed and replaced with fresh fuel. Reprocessing of spent fuel recovers any remaining uranium and plutonium for subsequent recycling as fuel. The fission products, small amounts of uranium and plutonium that are not recovered, and the other actinides which are not recovered (neptunium, americium and curium), comprise the high-level radioactive waste. If spent fuel is not reprocessed, entire fuel elements, including all of the actinides contained, ultimately become high-level radioactive waste [Ax77]. This waste, whether from reprocessing or in the form of spent fuel, includes radioisotopes having very long half-lives. The waste must eventually be placed in terminal storage repositories which prevent entry into the environment for up to tens of thousands of years.

Management of high-level radioactive waste must insure that the risk of detrimental effects from radioactive contamination of the environment is less than a level considered acceptable by society in relation to the various energy alternatives available. The toxic residuals and environmental disruption associated with use of the available alternatives to nuclear power also constitute a risk to society. Placing the risk of release of radioactivity associated with nuclear power into perspective requires recognition of the corresponding risks from the alternatives.

Assessment of radioactive waste management may be divided into two categories: 1) risk analysis, which considers both the probability of occurrence of each of various radiation release scenarios and the consequences of such releases, and 2) consequence analysis, which considers only the consequences of various postulated low-probability potential release events. In either category, there are various waste management options to consider and compare: 1) storage in alternate or other type sites, 2) alternate waste forms, 3) fuel reprocessing versus disposal of spent fuel, 4) efficiency of U and Pu recovery in reprocessing, and 5) partitioning of waste into different components for beneficial uses, transmutation of actinides to fission products in nuclear reactors [Bu75, Cℓ75, Cr77] and/or different terminal storage disposition. Any flexible assessment model must be applicable to any or all of these.

A flexible assessment methodology is needed for the evaluation of the various long-term waste disposal methods and management options [ERDA76a]. State and Federal regulatory and R&D agencies must be in a position to independently evaluate proposals for waste management activities in the course of carrying out their assigned functions including the protection of public health and safety and protection of resources.

In May, 1977, the International Atomic Energy Agency sponsored a major international conference on Nuclear Power and its Fuel Cycle at Salzburg, Austria [IAEA77], which resulted in reaffirmed commitments to nuclear power as an immediate substitute for fossil fuels and as a mature solution towards meeting the increasing global energy needs. The Salzburg conference also focused on the safe disposal of radioactive wastes from nuclear power as one of the most important parts of the nuclear fuel cycle that is yet to be fully established and demonstrated.

Presently, most countries that have nuclear power programs are studying the use of deep geologic formations for the safe emplacement of radioactive wastes. Only recently, two workshops were conducted to help provide exchange of scientific information between investigators involved in assessment work. A workshop on "Geologic Data Requirements for Radioactive Waste Management Assessment Models" [Lo76] sponsored by the Office of Waste Isolation for the U. S. Department of Energy (DOE) and arranged by The University of New Mexico, was held in June, 1976. A followup international workshop: "Risk Analysis and Geologic Modeling in Relation to the Disposal of Radioactive Wastes into Geologic Formations," sponsored jointly by the OECD Nuclear Energy Agency and the Commission of the European Communities, was held in Ispra, Italy in May, 1977 [OECD77].

The United States, Canada, and several countries in Europe have started modeling and risk analysis studies [OECD77]. In the U. S., as part of a recently-announced expanded national program in the management of commercial nuclear wastes, the National Waste Terminal Storage Program (NWTS) is underway by the DOE to provide federal repositories at multiple geographic locations with differing geologic formations in the continental United States for terminal storage of high-level radioactive waste [Mc76]. Formations being studied for possible location of terminal storage facilities include: bedded salt in western and midwestern states; dome salts in gulf coast states; shales, which are widely distributed over the country, and a wide variety of granites and other crystalline rocks and volcanic formations. The Los Medaños area in the Permian salt basin of southeastern New Mexico is under study for potential installation of a Waste Isolation Pilot Plant in bedded salt [Wr77]. The proposed pilot plant is for DOE trans-uranium waste and experimental retrievable emplacement of some high-level wastes. The Battelle Pacific Northwest Laboratories have started the Waste Isolation Safety Assessment Program (WISAP) for DOE [Bu76a, Bu77, Cℓ77]; the objective is to develop methods and generate data necessary to characterize the safety of generic geologic waste disposal concepts which are to be applied in the assessment of specific sites. At the Sandia Laboratories, a study is underway for the Nuclear Regulatory Commission (NRC) for application to repository licensing [Lo76, Ti77].

The U. S. Environmental Protection Agency (EPA) commissioned The University of New Mexico (UNM) to continue development and application of a Radioactive Waste Management Systems Model initiated at UNM in

1972 [Lo74a]. This model, implemented with a computer code, AMRAW (Assessment Method for Radioactive Waste), evaluates long-term environmental impact attributable to each phase of the waste management sequence. Emphasis in the study is placed on the terminal storage (disposal) phase. These various assessment programs including the UNM study for the EPA [Lo76, Lo77, Go77] have varying approaches and points of emphasis. This provides a complementary approach to waste management assessment and affords greater confidence in final results than would a single centralized effort. Related work is study of the Oklo Phenomenon [IAEA75,Bo76] which concerns several natural reactors which existed in a uranium deposit in Gabon, Africa 1.8 billion years ago. This constitutes a very old natural repository for radioactive wastes. Most of the radionuclides were retained in the immediate vicinities of the reaction zones. As the studies progress, the Oklo data may serve to provide some validation of the assessment models.

This volume is one of four which report on the UNM radioactive waste management assessment method and its application. The purpose of this overall study for the EPA is to complete development of the model for technology assessment of radioactive waste management, including the AMRAW computer code, and to demonstrate the model for one model repository site. This demonstration includes sensitivity and consequence analyses for the terminal storage phase, a preliminary demonstration for the repository operations phase and for terminal storage in another geologic setting. The study also evaluates the feasibility of applying the model to other radioactive and nonradioactive hazardous materials.

The scope of the study involved approximately 6.5 man-years of effort. This was interdisciplinary, with the central effort in the Chemical and Nuclear Engineering Department of The University of New Mexico and a major component effort in the Economics Department. Support was provided by the Departments of: 1) Geology, 2) Biology, and 3) Electrical Engineering and Computer Science. Additional supporting effort was by the Department of Geoscience at the New Mexico Institute of Mining and Technology and Geohydrology Associates. Much helpful information was obtained from national laboratories (see the acknowledgements section for details) and individuals who reviewed earlier draft reports.

CHAPTER 2

SUMMARY

A Radioactive Waste Management Systems Model proposed by The University of New Mexico has been developed and implemented under this contract. The assessment model and associated computer code is called AMRAW (Assessment Method for Radioactive Waste). The full model includes the several phases in the waste management sequence: residuals treatment (interim surface storage and solidification), waste transport, repository operations, terminal storage, and any other intermediate phases which may become applicable. The effort during this study has concentrated on terminal storage, but a preliminary application to repository operations is included.

AMRAW is divided into two parts which are run separately: 1) AMRAW-A consists of the Source Term (Inventory at Risk), the Release Model, and the Environmental Model, and 2) AMRAW-B is the Economic Model. AMRAW-A, described generically in this volume, uses externally-generated values of input parameters for potential geologic and man-caused release events, transport from points of release to the environment, environmental pathways to man and calculation of radiation doses.

The radiation dose rates determined by AMRAW-A are input to AMRAW-B, described in Volume III. The Economic Model in AMRAW-B determines incidence rates of health effects corresponding to calculated dose rates, determines the associated costs, and attributes these costs to radionuclides, related groups of nuclides, and to elements initially in the waste inventory. Initial inventory for the terminal storage phase of waste management refers to the accumulated quantities at the end of the repository operations phase. Up until that time, risk reduction options of improved recovery and/or partitioning may be applied [Cℓ75, Bu75], Cr77]. The allocated costs from the Economic Model provide a common reference base for summing up the consequences of a number of health effects associated with many different radionuclides, with consideration of the population affected, agricultural activities, and other factors. In addition to comparisons between disposal options, feedback of these calculated costs to the fuel reprocessing and residuals treatment phase provides a basis for comparison of reprocessing and waste partitioning options. Due to uncertainties in data values and the difficulty in assigning dollar costs to health effects, calculated results are not represented as being a precise quantification of damage costs. As use of the model proceeds and improved input data becomes available, it may become appropriate to apply the results more directly to cost/benefit evaluations.

In the model, released radioactive material is dispersed to environmantal input receptors (air, ground surface, surface water, and ground water) in each geographic zone in a study region around a repository. The input factors which define the dispersion are determined externally to AMRAW. Concentrations are accumulated in each environmental receptor but adjusted during each time increment for transfers between receptors, radiodecay and buildup and environmental removal processes. In the results reported in Vols. II and III, most of the cases use a conservative environmental half-time of 30,000 years in lieu of data to support shorter times. The corresponding token value of environmental decay constants is believed here to be unrealistically low and leads to overestimating the persistance of released radionuclides and the resulting dose rates. Sensitivity analysis cases reported in Vol. II investigate the effect of lowering the environmental half-time. Research is needed to determine nuclide-dependent environmental behavior to justify the use of more realistic values for environmental half-times and to thereby obtain improved calculations of estimated environmental concentrations as functions of time.

AMRAW-A calculates the radiation dose commitment rate via pathways for direct exposure of the population in each zone and for food and drink pathways. A unique feature of the model divides the pathways and resulting dose rates into local dose (to the specific local population groups) and nonspecific dose. The latter is from agricultural products which are largely exported; the nonspecific population affected is outside of as well as within the study region.

The remainder of this chapter applies primarily to the terminal storage phase. As described in Section 4.C, AMRAW may be run for any of several release scenarios. When run for a discrete geologic event (or combination of events) occurring at a specified time, the results are a measure of consequences associated with the event and time of occurrence. Varying the events and times of occurrence comprises a consequence analysis. In this mode of operation, the problems of predictive geology are largely bypassed, but a number of difficulties do remain. For example, if a volcano penetrates a repository, what fraction of intercepted waste inventory is pushed aside or remains within magma in a buried configuration and what fraction becomes expelled by volcanic ejection? Further, for the material ejected, what particle size and chemical form distributions may be expected? In cases reported in the other volumes of this report, it is assumed that one-half of intercepted inventory is ejected without reburial and that all material ejected into the atmosphere is of small particle size (effective deposition velocity 0.01 m/s), and is of a physical and chemical form which is immediately available to environmental processes. While it is believed here that these are overly conservative assumptions, research has not been done to provide better data.

When AMRAW is run in a mode which distributes release events probabilistically over time, the results are a measure of risk associated with the events and repository properties. Risk is defined as the product of the "Probability of an Event" and the "Consequences of the Event." Varying event scenarios, repository conditions, waste inventory, waste forms, or other factors comprise a risk analysis. In this mode, calculated values of environmental concentrations and dose rates (or in AMRAW-B, health effects and associated costs) at the various times do not represent predicted values. For example, a volcanic event with an estimated rate of occurrence of 2×10^{-12}/y distributed probabilistically spreads the event over $1/(2 \times 10^{-12}) = 5 \times 10^{11}$y. Thus, while the probabilistic method assigns some annual probability of volcanic explosion and obtains associated radiation dose rates and resulting health effects to the population, it should be observed that the low probability means there is only one chance in 500,000 ($5 \times 10^{11}/1 \times 10^{6} = 500,000$) that such a volcanic event would expel material at any time during a one million year storage period. The calculated results, using the probability of occurrence and consequences of interest such as environmental concentrations, applicable dose rates or health effects, give the risk and provide a basis for comparing options with an objective of minimizing risk. Another mode in which AMRAW can be run in the future is to use data from dynamic repository simulation (see paragraph 4.C.1.d) when results become available from persons developing the analysis concept.

There are difficulties in predicting geologic events over long periods of time into the future. Gould [Gℓ65a,Gℓ65b] discusses an outmoded term: the concept of "substantive uniformitarianism" which postulates uniformity of rates or material conditions. This concept, which assumes that changes which occurred in the past continue invariantly through the present into the future, is considered by Gould to be incorrect in any strict formulation. A concept which assumes spacial and temporal invariance of natural laws has been termed "methodologic uniformitarianism." This is a basic mode of inductive reasoning in various fields of science. Longwell [Gℓ65b] suggests replacing this term by "uniformity of process through time," and Gould [Gℓ65b] suggests simply: "inductive inference." Workshops dealing with geologic data for risk assessment [Lo76, OECD77], have considered both gradual processes and sudden discontinuous events. AMRAW input data for the probabilistic mode does not depend upon any particular predictive concept (see Section 4.C). Demonstration of the model to date has depended largely upon projection of processes of the recent past. As advances in predictive geology are made AMRAW is ready to accept the data. It should be recognized that uncertainty in the results increases as the length of time into the future increases. While absolute predictions of environmental contamination and population dose rates are limited by the geologic uncertainty, as well as other relevant future conditions, AMRAW results are particularly adapted to: 1) comparison of management options for risk reduction purposes, and 2) scoping of geologic event importance by running the model for ranges of probability or dynamic scenarios. Uncertainties in probabilities or omissions of events which are expected to apply equally to two cases being compared tend to cancel when making relative comparisons. Sensitivity analysis discussed in Vol. II demonstrates these capabilities.

Among the various geologic disruptive events is a leaching incident, in which ground water gains access to a portion of the waste inventory. The leach rates following the start of a leaching incident are calculated as a function of time within AMRAW using radionuclide-dependent input parameters. A method for estimating the input effective diffusivity is presented. Subsequent transport through the geosphere in ground water is calculated for appropriate time intervals within AMRAW for each radionuclide. The paucity of data for distribution coefficients (K_d) for specific sites and ground water qualities introduces uncertainty into the ground water transport calculations. The ingrowth of decay products during ground water transport is presently handled by an approximate method. One nuclide at a time is carried through the AMRAW calculations. When a particular radionuclide from a decay chain is considered, leaching and ground water transport calculations are first made on the basis of the average inventory of that species present in the waste during an increment of leach time. Then the quantity at a given time and distance is adjusted by a factor which accounts for net decay or ingrowth of the species, considering the total waste inventory. If precursors have the same leach rate and K_d as the species of interest, these precursors appear in the leachant and move along with the species; the calculation of ingrowth in this case is exact. The method becomes approximate when precursor leach rates and K_d values are different than those for the decay product of interest.

The AMRAW model and code calculates radiological environmental impact for geological and man-caused disruptive scenarios ranging up to catastrophic events such as volcanic eruptions and meteorite impact. Whether radiological effects or damages are important relative to the nonradiological devastation has not been studied. AMRAW calculates radiological effects from the moment each disruption occurs, assuming the population stays in place and is not affected by physical violence of the event. This is, of course, conservative and a more accurate evaluation would insert a phase lag before substantial reinstatement of local population. This is an area of research which would be very helpful to risk analysis of natural disasters as well as nuclear risk analysis.

Volume II presents specific discussions of input data sources, assumptions and limitations for: 1) a base case for a repository in bedded salt, 2) other cases demonstrating sensitivity and consequence analyses, 3) a case demonstrating application to another geologic setting, and 4) application of the model to repository operations and ground surface storage. Volume III presents corresponding discussions for the Economic Model. It should be noted that the work covered by this report is not represented as being complete in regard to potential release mechanisms but is intended to demonstrate the degree of flexibility. There is a rapidly changing data base which can be repeatedly applied for updating the results. AMRAW is a tool to aid management decisions, but it does not replace the need for extensive studies at each proposed repository site. The model can incorporate results of such site studies for continuous refinement of results.

CHAPTER 3

CONCLUSIONS AND RECOMMENDATIONS

The AMRAW model is interdisciplinary and successfully brings together results from several fields of study for technology assessment of each phase of radioactive waste management. The model uniquely links each step from an inventory of radioactive waste through releases into the immediate environs, transport and dispersion to environmental receptors, pathway analysis for estimates of resulting dose-to-man, and calculation of corresponding health effects. This sequence is handled as a continuous calculation with output of intermediate results providing released quantities, environmental concentrations, doses to population, and numbers of health effects. The AMRAW-A part carries the calculation sequence through dose rates and the AMRAW-B part picks up from there and calculates health effects.

AMRAW does not replace but instead uses established models for various segments of the problem, such as air dispersion, geosphere and biosphere transport, environmental pathway analysis, and dosimetry. The existing models or published results from their use, augmented by the judgements of experts in each discipline are externally used to prepare extensive input arrays and individual items of factors or coefficients used in AMRAW. Individual calculation steps in AMRAW generally involve multiplication of sequences of related factors and adding to accumulate parallel contributions, plus use of other simple functions for time-dependent adjustments. While the individual steps are simple, the bookkeeping is quite complex. AMRAW provides a structural means for orderly processing thousands of data items and keeping track of intermediate and final results for various forms of output display. Two processes, leaching and ground water transport are handled analytically within AMRAW by subprograms (RLEACH and CRATIO, respectively). These subprograms depend upon input data from laboratory and field studies. Other subprograms do the bookkeeping to process input data for releases (FAULT), transport to the environment (TRINP) and pathway analysis (TRMAN). Where preferred, the leaching and ground water transport subprograms can be replaced by alternate subprograms which process input data obtained by external use of more rigorous codes. This alternate has not been done during this study but the modular structure of AMRAW provides flexibility to do so.

Applications of AMRAW, presented in Vols. II and III, necessarily make use of data which has been available early in assessment efforts. Continuing studies of proposed repository sites in various geologic formations, measurements of site-specific sorption properties, and advances in predictive geology can provide updated input for AMRAW to refine and extend the applications. The results obtained to date are not claimed to represent all disruptive or other release processes which potentially could occur. However, the probabilistic or risk analysis mode, with consideration of the most disruptive events envisioned, obtains results which suggest that only a minor risk is associated with the model repository studied. Consequence analysis results indicate that intersection of a repository by a volcano after 1000 y or later, through highly unlikely, could result in population doses in areas close to the site which exceed regulartory limits but not at a lethal level.

The AMRAW model, developed for applications to various phases of radioactive waste management, may also be applied to other nonradioactive hazardous wastes or various pollutant spills. Application to seabed disposal by redefining environmental receptors and making other modifications is a possibility through this has not been studied.

It is recommended that improved and more comprehensive data be obtained in areas of: 1) distribution coefficient (K_d) and its dependence upon geologic media, pH, oxidation potential, and other ground water properties, 2) environmental decay, which relates to removal and retention mechanisms which reduce the environmental concentration of a nuclide with time, independent of radiodecay, and 3) resuspension from land surface into the air. In addition, improved water usage and hydrologic information is needed. New data and improved geologic disruptive event descriptions should be input to AMRAW to update the earlier runs.

Preparation of alternate subroutines for leaching and ground water transport to process data externally generated by other codes is suggested.

There are several types of AMRAW applications recommended for further work. The model should be applied to various proposed repositories in different geologic media: shale, basalt, granite, and dome salt. Different emplacement methods such as drilled hole matrix and conventional mining may affect the results and should be investigated. An application which can help to place results obtained to date into perspective is the calculation of risk associated with an undisturbed uranium ore body. This is a naturally radioactive "repository" of low concentration but having a large area.

The increase in long term environmental risk if unreprocessed spent fuel is disposed of as high-level waste, instead of disposing only reprocessing waste, should be assessed. Partitioning and transmutation alternatives, and improved reprocessing separation should be assessed.

Above all, it is recommended that important categories of risk assessment be completed promptly and decisions be made to resolve radioactive waste management questions.

CHAPTER 4

GENERIC DESCRIPTION OF AMRAW-A MODEL

The Radioactive Waste Management Systems Model (Fig. 4-1) has several parallel paths, each representing a phase in the waste management sequence: residuals treatment (interim surface storage and solidification at a reprocessing plant site), waste transport, repository operations, and terminal storage. If other phases become applicable, such as interim surface storage away from a reprocessing plant site, interim storage as spent fuel, reprocessing of waste form, and other transportation steps, each of these simply becomes an additional parallel path in the model.

Implementation of the model is by the AMRAW computer code. The code runs calculations separately for each branch of the model. Input data includes a flag (IW) which designates the model branch for which the data applies. This flag controls routing within the code to handle some variations in calculations which depend upon the waste management phase being studied. Most of the current effort is applied to the terminal storage (disposal) branch (see Part 1 of Vol. II). A preliminary demonstration of application to the repository operations branch is included in Part 2 of Vol. II.

The model is basically a computer simulation or systems analysis model; a basic assumption is that each system studied is linear. AMRAW does not replace established models which are in use for various segments of the problem, such as air dispersion, geosphere and biosphere transport, environmental pathway analysis, and dosimetry. Instead, most of the calculations within AMRAW make use of input arrays and matrices of factors or coefficients obtained from the established models, augmented by the judgements of experts in each discipline. Simplified versions of leaching and ground water transport models are used internally, but these as well as the major model sections (Fig. 4-2) are each contained in subprograms, providing for replacement should this become desired. Output from AMRAW-A is provided at several stages through the model giving calculated release quantities, environmental concentrations, and doses to population.

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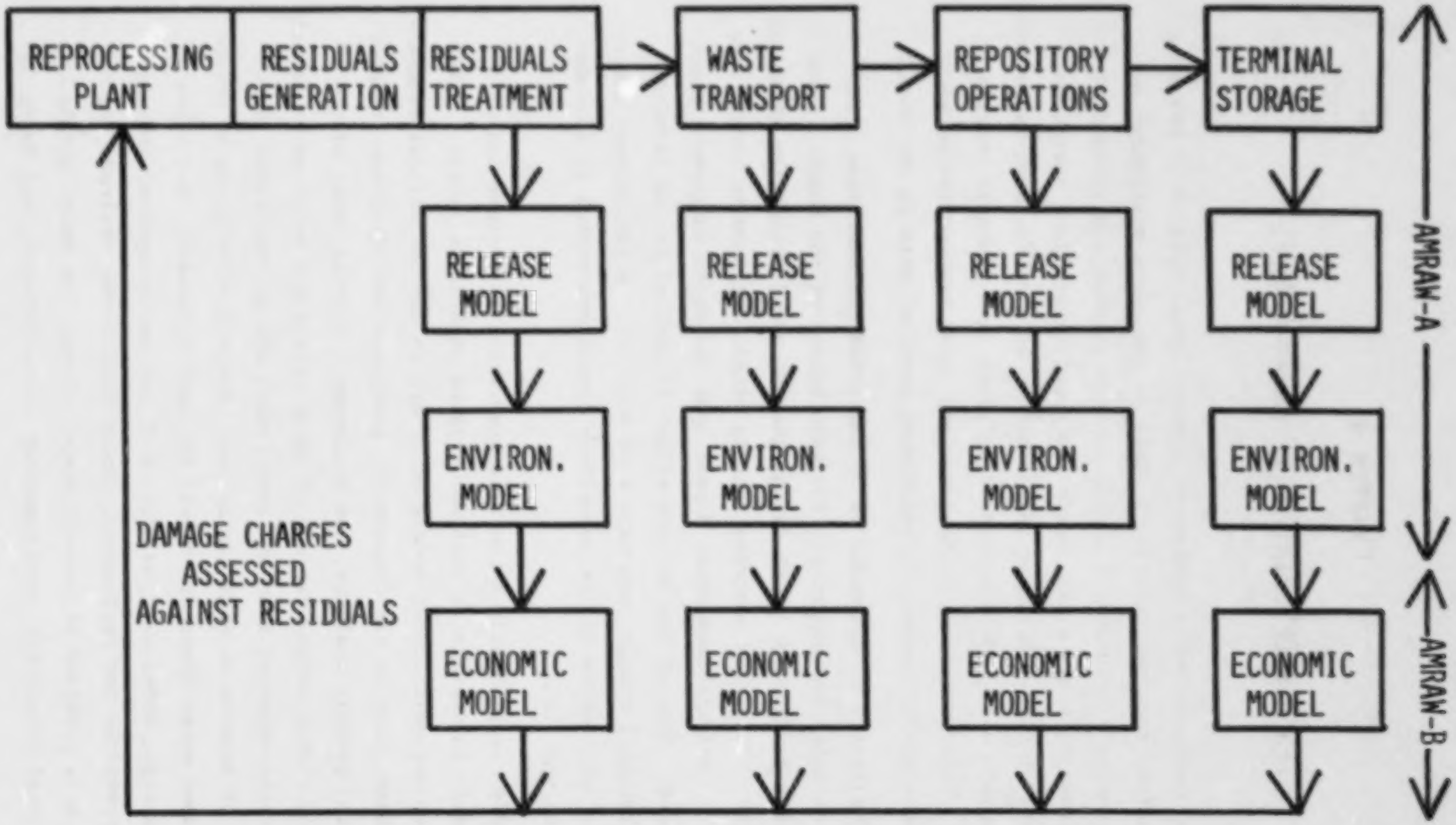


Figure 4-1. Radioactive waste management systems model.

AMRAW-A interfaces the component models providing continuous calculations from the Source Term (Inventory at Risk), through the Release Model and the two parts of the Environmental Model (Transport to Environment and Environment-to-Man Pathways), obtaining output doses to population. This output is the major input to AMRAW-B which then calculates health effects and the corresponding damages in economic units. The two parts of AMRAW can be linked together for a continous run, but it has been convenient to maintain them separately for development purposes and parametric studies.

Further, AMRAW is a compartment model; a compartment model assumes that the various components of the system can be lumped into compartments and that all changes and movements can be accounted for by transfer coefficients between compartments. The component models shown in Fig. 4-2 determine the transfer coefficients which link the various compartments and receptors in sequence. Table 4-1 summarizes the sequence of calculated quantities and transfer coefficients. In the model, the various compartments and receptors are split into parallel sets: 1) the inventory divides into a number of radionuclides, each varying with time, 2) environmental input receptors are air, land surface, surface water and ground water, and 3) dose commitment rates divide into local dose rates in each geographic zone and a nonspecific category explained later, and further divide into dose rates to various body organs. The are implied intermediate receptors which are not specifically collected for output. An example is a contaminant concentration in food. This is lumped into the environment-to-man pathways model component which includes a food intake factor and a dose conversion factor in addition to a food concentration factor, for each pathway and nuclide. Operated in a risk analysis mode, it is assumed in AMRAW that risk is defined as the product: probability of occurrence of an event, multiplied by the consequences should the event occur; operated in a consequence analysis mode, consequences are evaluated for discrete events occurring at specified times. The mode of operation is dictated by the nature of the Release Model input data.

The following sections in this chapter describe the AMRAW-A part of the model, and the component models in AMRAW-A in detail; Vol. III

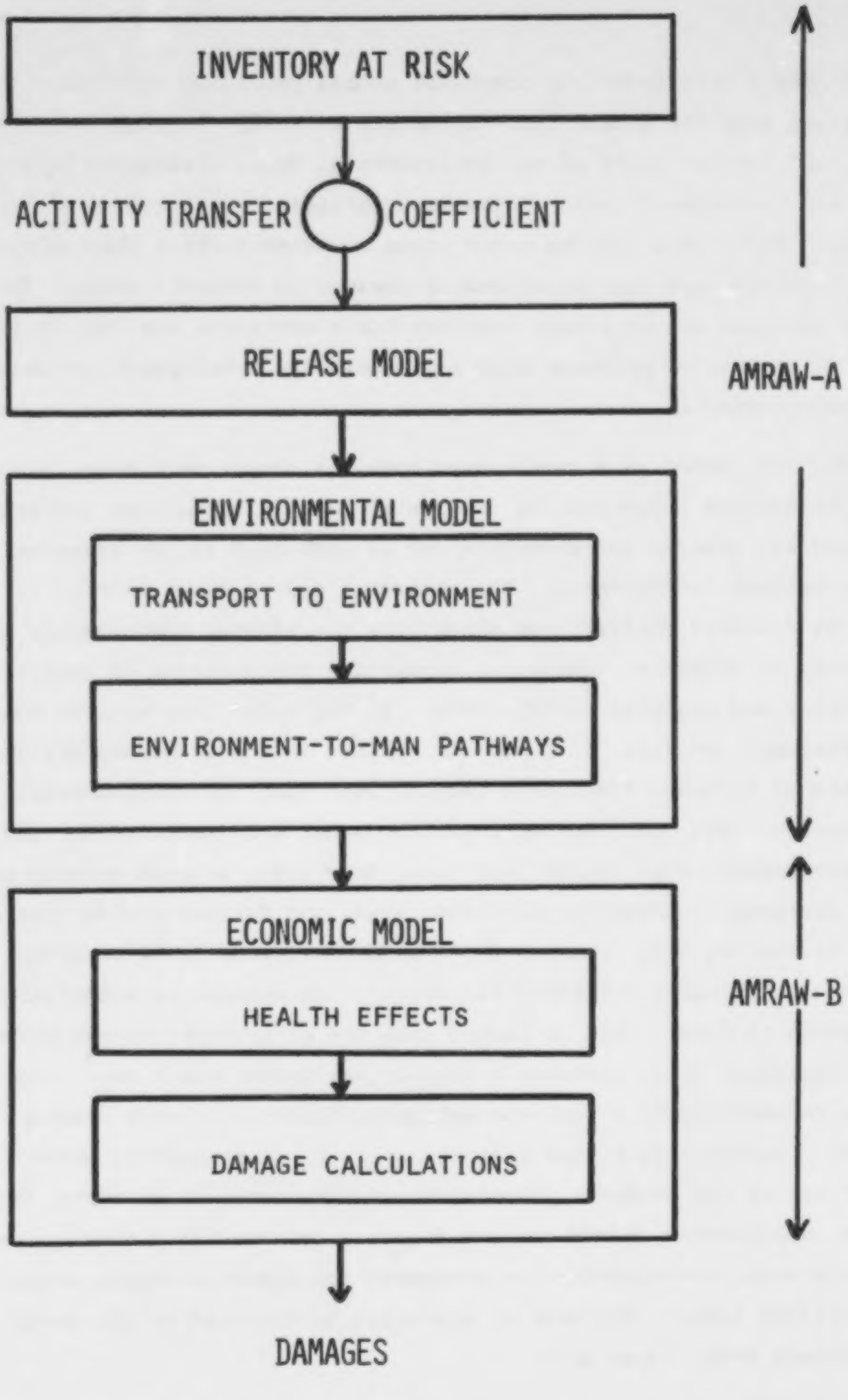


Figure 4-2. One branch of systems model.

Table 4-1. Receptor and Transfer Coefficient Sequence in AMRAW

Compartment or Receptor	Transfer Coefficient
AMRAW-A	
Inventory, grams	
	Specific Activity
Inventory, Curies	
	Release Probability and Release Fraction
Preliminary Environmental Input Receptors	
	Transport to Environment
Environmental Input Receptors	
	Environment-to-Man Pathways
Dose Commitment Rates	
AMRAW-B	
	Health Effect Incidence Rates
Health Effects	
	Health Effect Costs
Economic Valuation of Damages	

describes AMRAW-B (Economic Model).

A. AMRAW-A MODEL

The AMRAW-A part of the AMRAW computer code may be run for one or more branches of the model, depending upon the number of sets of input data provided. As stated earlier, each data set includes a flag (IW) which designates the model branch for which the data applies. The discussion which follows in this volume is based upon the terminal storage branch, in that the frame of reference refers to the inventory emplaced in a repository. However, the calculation flow of the model and code also applies to the other branches. When applications are made to other branches, some programming changes may be needed such as addition of alternate calculation routing or additional subprograms.

The total period of time to be studied is divided into time increments each of which is identified by the time (in years) at the end of the increment. Various time-dependent parameters are averaged in each time increment as the calculations proceed. The AMRAW code runs one nuclide at a time, considers one time increment at a time for calculation of releases, and follows the migration of each such release increment through all subsequent time increments "in the environment." Then, for each time increment, net concentrations are accumulated for all prior (or coincident) release increments. The number of times and their values, specified by input data, must be a compromise between calculation resolution (small time increments) and computer storage, output bulk and running time limitations (large time increments). Present applications divide one million years into 50 times with 5 y increments at the beginning, increasing in steps to 100,000 y increments after 100,000 y.

Each branch of the model (Fig. 4-2) is entered with the mass of each significant radionuclide in the inventory at risk at each time (see Section 4.B). This is converted to Curies in the inventory by an activity transfer coefficient (specific activity). It is assumed that most of the risk associated with a given inventory of radioactive waste can be represented by a fraction of the total number of nuclides present. This is based on the finding that fewer than 25 nuclides represent most of the total of a hazard measure evaluated for the total inventory. The handling of the nuclide inventory by AMRAW assumes that the total inventory versus time is not affected by movement of portions of the inventory. That is, as postulated migration proceeds, the total inventory of each nuclide at any time is equal to the inventory if no migration occurs. This is a valid assumption in itself but it leads to some errors in estimates of distributions when precursors and daughters do not migrate together.

The Release Model calculates the probability for release by each of numerous potential release mechanisms, and the fraction of the inventory released by each such occurrence, during each increment of time. As described in Section 4.C, AMRAW may be run for any of several release scenarios: 1) probabilistic distribution of events over time, 2) discrece event at specified time, 3) several events each at mean time of first occurrence, 4) dynamic repository simulation, or 5) combinations of these. Release calculations are totally dependent upon input parameters; AMRAW does not possess predictve capability for geologic events. Modeling done externally to AMRAW, plus professional judgement of experts in fields of geology and hydrology are needed to define the data input for this part of the AMRAW model. Each event or combination of events must be defined by the product of one or more time-dependent factors. During each release time increment, AMRAW determines the fraction of inventory of a given nuclide released by each event, and superimposes and accumulates for all events as defined by the input data. This process is repeated in turn for each of the environmental receptors: air, land surface, surface water, and ground water. Uncertainty in prediction of geologic events appears to be the greatest limitation of assessment models. Leaching, following contact of waste by ground water, is calculated within AMRAW by a subprogram. This subprogram indicates relatively high leach rates initially, decreasing to a lower constant rate after some time. Input parameters are based upon short-term leaching experiments, resulting in error for long-term projections.

Releases as determined by the Release Model are not necessarily directly to the environment. This is particularly true for deep releases to ground water. The first portion of the Environmental Model (see Section 4.D.1) is therefore the "Transport to Environment" section. This adjusts each release increment, obtaining the contribution-to-concentrations in environmental input receptors at various times following release. These receptors are: air, ground surface, surface water, and ground water. It is assumed that the environment can be represented by these 4 receptors. Increased complexity could divide land surface into surface and subsurface categories, for examples. The adjustment provides for dispersion into each of the four receptors in each of the several geographical zones comprising the study region, and then converts accumulated activities to concentrations by accounting for dispersion areas or volumes in each zone. The dispersion to receptors in each zone uses factors furnished as input data. Air dispersion factors can be based upon runs with an air transport code or a simplified analytic method. A basic limitation here is the predictability of long-term meteorological conditions. Dispersion associated with direct releases to land surface is not well modeled at this time; input for current applications has used a simple exponential distribution. The adjustment also accounts for decay from the time of release to the time being evaluated, transfer between receptors (such as deposition from air onto ground), retardation in ground water flow, and other environmental removal or fixation processes. Ground water transport is calculated within AMRAW by a subprogram which uses a simplified one-dimensional flow model with two-dimensional dispersion. This assumes equilibrium conditions for all related physical processes. Required data includes aquifer porosity, longitudinal and transverse dispersion coefficients, ground water seepage velocity, and the distribution coefficient K_d for each nuclide. Chain decay for nuclides in decay series is handled by an approximate technique. If a more rigorous treatment becomes necessary, an external code should be used to prepare input data for AMRAW. In this case, an alternate subprogram in AMRAW would be required to process data such as by simple polynomials.

The last portion of the Environmental Model (see Section 4.D.2) covers the pathways from environmental input concentrations to radiation dose to the population, with dose rate calculations for several organs of concern. This part of the model considers each environmental receptor in turn and each of two main pathways for each: 1) air: immersion and inhalation, 2) land surface: direct surface exposure and ingestion of terrestrial food, 3) surface water: submersion and ingestion of drinking water and aquatic foods, and 4) ground water: ingestion of drinking water. In addition, each main pathway is divided into an appropriate number of subpaths reflecting, for example, various categories of foods. Calculations accumulate over the several subpaths under each receptor and results are not output for each main pathway or subpath. Dose rate results for paths which affect residents in a particular zone are accrued as "local dose rates." Examples are from air immersion and inhalation, direct surface exposure, and ingestion of drinking water. Dose rates associated with exported agricultural products are accrued under "non-specific dose rates." Evaluation of each pathway obtains the transfer coefficient between an environmental concentration and dose-to-man by considering: 1) a biofactor where appropriate to account for concentrations in food relative to an environmental concentration, 2) a factor expressing consumption, exposure time fraction, or food production rate, and 3) the appropriate dose conversion factor. Assumption of a linear system permits superposition of effects such as environmental concentrations and dose rates from several pathways.

The AMRAW code is structured with sequences of compartments linked by transfer coefficients (Table 4-1). The receptors represent the progress of releases, environmental concentrations, concentrations in food and drink, radiation doses, health effects and associated economic damages. The transfer coefficients are evaluated in subroutines using externally-determined input data. The subroutines can be modified or replaced, providing a modular arrangement. The philosophy is to keep AMRAW as simple and straightforward as possible to avoid "black box" mystery. Factors for dispersion, biological accumulation, dose, etc., used in the transfer coefficients, are evaluated externally by various existing transport and dose codes. Calculation of leach rates and coefficients expressing ground water transport are both performed analytically in subprograms in AMRAW. Each of these can be replaced by alternate subprograms if that need develops. One example of this is the use of a more sophisticated code for ground water transport. Such a code would be prohibitive as a subprogram in AMRAW due to excessive computer time when called thousands of times during a run, but a simple polynomial or other scheme can be utilized in an alternate AMRAW subprogram to process input parameters generated externally by the more sophisticated code. The AMRAW code serves as a vehicle for bringing together data from several disciplines in an organized manner.

The calculation sequence used in AMRAW is to consider one nuclide at a time, carrying each through all of the calculations discussed above for the release and transport to environment parts of the model, leading to net environmental concentrations in each receptor in each zone at each time evaluated. This is repeated for each nuclide, generating the complete environmental concentration array before proceeding to the environment-to-man calculations. For the pathway analysis, each nuclide is again considered one at a time, at each time over the time period studied, developing the dose rate arrays.

The following sections of this chapter provide details of each of the sequential steps in the AMRAW-A part of the code. Section 4.E gives a mathematical summary of the model.

B. SOURCE TERM

Assessment of potential releases from a radioactive waste repository and the consequences of releases requires a definition of the quantity of waste present, the quantity of each significant radionuclide, and the variation with time due to radiodecay. The quantity of material at risk is the "source term." This is indicated in Fig. 4-2 as "Inventory at Risk." It should be noted that the "source term" as used in this study represents the total inventory of each radionuclide considered, at the various times of interest, whether totally confined within the repository or whether portions are in transit through the geosphere and/or biosphere. In some other studies the source term refers only to quantities released to the geosphere and/or biosphere.

If all of the radionuclides of interest were in simple one-step decay, initial quantities as input data would be adequate, with subsequent quantities calculated within the code. However, the actinides and their daughters, here referred to as "heavy metals," are in complex decay chains. The quantities of some isotopes in decay chains increase over time, reach a maximum and then display a net decrease through decay as precursors decay. Instead of performing the complex calculations within AMRAW, they are handled externally by any specialized code developed for the purpose, and the quantities of each nuclide at selected times are input to AMRAW. In this study, data calculated by ORIGEN, the Oak Ridge isotope generation and depletion code [Bℓ73] is used. Currently, fifty times are used between the start of repository operations and one million years, with shorter time intervals at the beginning and increasing time intervals later. The times used are specified as input parameters and may have any desired values, in years. The number of times are limited only by computer storage, running time, and output cost considerations.

In general, sources of nuclide quantity data do not correspond to the desired times for AMRAW input. Codes such as ORIGEN calculate gram quantities at specified times but available output from other studies usually has different times than those selected for an AMRAW application and/or have insufficient intermediate values. Adjustment of these times and addition of intermediate values may be accomplished with any adequate curve-fitting method. Cubic spline functions are a recent mathematical development and provide an excellent method for curve-fitting. Basically, the technique involves interpolation by cubic splines such that a cubic polynomial function is formulated between each pair of data points. Coefficients are chosen so that the second derivative is continuous across adjacent points. A cubic spline curve-fitting computer program developed by Moler (The University of New Mexico Mathematics Department) and Malcolm [Fr77] was obtained and slightly modified for time adjustment of nuclide concentration data for this study. The auxiliary program for the purpose is called "POLYEPA."

The inventory of radioactive waste from spent nuclear fuel initially includes up to several hundred radioactive isotopes. Many of these are present in small quantities or have short half lives and do not make a significant contribution to the total hazard. A screening method [Lo74b] is applied to select the most significant radionuclides over the time range of interest, to reduce the calculations by AMRAW to a more manageable level. The screening method uses a hazard measure defined as the activity in Curies of a given radionuclide in a quantity of waste (such as from one metric ton of fuel) divided by the corresponding Radiation Concentration Guide (RCG) value [CFR20]. Ingestion hazard uses RCG values for water and inhalation hazard uses RCG values for air. The ORIGEN code outputs tables of these hazard measures. Briefly, the screening method considers numerous times over the full time range of interest. The three fission product elements and three heavy metal elements with the highest hazard measure are selected at each time considered. Then the isotopes are selected which collectively comprise over 99% of the hazard for each selected element. This method provides representation from the two major categories of elements in the waste and representation over the entire period of time studied. During initial work on this study, a waste blend 80% from enriched uranium fuel and 20% from self-sustaining plutonium recycle fuel was assumed. The screening method applied over a time range of 10 years to one million years selected 7 fission product isotopes of 6 elements and 16 heavy metal (actinides and daughters) isotopes of 7 elements. Because of special environmental interest in

C-14 and I-129, these were added for the repository assessment, making a total of 25 radionuclides for assessment, listed in Table 4-2.

Table 4-2. Selected Significant Radionuclides

Fission Products

C-14[a]	Sr-90	Zr-93	Tc-99	I-129	Cs-135
	Y-90	Nb-93m			Cs-137

Heavy Metals

Thorium Series	Neptunium Series	Uranium Series	Actinium Series
Cm-244	Pu-241	Am-242m	Am-243
Pu-240	Am-241	Cm-242	Np-239
	Np-237	Pu-238	Pu-239
	Th-229	Th-230	
	Ra-225	Ra-226	
		Pb-210	

[a] The activation product C-14 is included with fission products.

Table 4-3 summarizes the percentages of total ingestion and inhalation hazard measures represented by the two major groups of the 25 selected nuclides and their total. It may be noted that the selected nuclides represent 96% or more of the total hazard for the fission products group, the heavy metals group and the total of all nuclides over a range of waste age up to one million years. This time range includes the peak buildup quantities and the start of net decay for the most persistent of the selected nuclides, including Ra-225 which peaks at between 600,000 and 700,000 years. The small balance from all of the nuclides not selected represents less than a few percent of the total hazard. Values of 100% indicate a contribution from all other nuclides of less than 0.05%. AMRAW may be applied over any appropriate time-range; the one-million-year range used in this study does not necessarily indicate a required isolation period for stored radioactive wastes but was arbitrarily chosen as a starting basis for calculations.

Table 4-3. Fraction of Total Hazard Represented by Groups of Selected Radionuclides, Percent

	Waste Age, Years					
	10	10^2	10^3	10^4	10^5	10^6
Ingested Hazard						
Fission Products[a]	100.00	99.6	100.0	100.0	100.0	99.0
Heavy Metals	99.5	99.2	97.4	96.7	96.1	95.6
Total	100.0	99.5	97.4	96.7	96.2	95.6
Inhalation Hazard						
Fission Products	98.2	99.6	98.1	100.0	100.0	100.0
Heavy Metals	99.8	100.0	98.3	97.7	98.8	98.9
Total	99.7	100.0	98.3	97.7	98.8	98.9

[a] The activation product C-14 is included with fission products.

Next, some discussion of the relationships between the nuclear power generation scenario and the corresponding waste accumulation is necessary. Some variation of constituent nuclides in spent fuel occurs with variations of irradiation history and with the type of fuel. Light water reactors (LWR) are fueled with enriched uranium in which the fissile isotope is U-235. However, about one-third of the fissions in LWR's are plutonium fission, primarily fission of Pu-239 formed by conversion of U-238 by neutron capture during the fuel lifetime in the reaction. Recycle of plutonium recovered by reprocessing of spent fuel results in an increased fraction of fissions of plutonium in an LWR. A high temperature gas-cooled reactor (HTGR) is initially fueled with U-235 and utilizes conversion of thorium into fissile U-233. Slight differences in the fission yield spectrum for the several fissile species results in a minor effect on the fission product accumulation as compared to the LWR case. The main result from fuel cycles involving increased plutonium utilization, as in Pu recycle in LWR's or the liquid metal cooled fast breeder reactor (LMFBR), is an increase in the amount of heavier actinides such as americium and curium produced by non-fissioning neutron absorption. If there is no reprocessing of spent fuel, the spent fuel itself becomes radioactive waste [Ax77], increasing the amount of U and Pu to be disposed of by a factor of approximately 200 over the 0.5% assumed for reprocessing waste; reprocessing is generally assumed to recover 99.5% of U and Pu. The amount of waste from nuclear power generation is, of course, proportional to the thermal energy produced, which can be expressed as

$$E_{th} = P_e tF/e_{th} \qquad (4\text{-}1)$$

where

P_e = rated electrical power capacity

t = duration of time period

F = capacity factor (average operating fraction of rated capacity during period)

e_{th} = thermal efficiency.

Any consistent set of units may be used. Fuel burnup is expressed in terms of thermal energy produced per metric ton of heavy metal in the fuel loading. A typical design value used for LWR's is 33,000 Mw-d/MT. For more detailed discussions of the relations between fuel cycles and corresponding waste accumulations, the reader is referred to projections of waste generation by Blomeke, et al. [Bk74, KeC76].

The source term for AMRAW input is preferably based upon a scenario which details installed capacity of each reactor type versus time, reprocessing status, interim storage periods, and other factors which determine the quantities of significant constituent radionuclides [Sℓ77] placed in a repository to be assessed. The projected quantities versus time accumulated in the repository are required for assessment of the "repository operations" phase. The total accumulation is required for assessment of the "terminal storage" phase. Results calculated for the repository can then be normalized and presented in terms of damage (environmental concentrations, dose rates, or other calculated results) per unit of energy production, per unit of fuel, per reactor year, or per unit of waste emplaced. It should be noted that estimation of probabilities for disruption of events depends upon the respository size or area involved for storage of waste. This dependence upon repository size makes it difficult to run AMRAW for, say, waste from one metric ton of a particular fuel type. Comparisons between different reactor types, fuel cycles, reprocessing conditions or other considerations can be accommodated in AMRAW by assuming a model repository is filled, in turn, by waste from each system to be compared.

In summary, the source term for AMRAW is a matrix of grams of each significant radionuclide over a sequence of specified times. This matrix is prepared externally to AMRAW in accordance with any nuclear power scenario to be assessed and furnished to AMRAW as input data. If this matrix includes the times during which waste is being placed in a repository, AMRAW may be operated for the "repository operations" phase as well as for the "terminal storage" phase. Conversion to Curies of activity is accomplished within AMRAW by multiplying an item in the source term by the corresponding specific activity (activity transfer coefficient in Figure 4-2) which is input to the code for each nuclide considered.

C. RELEASE MODEL

The first step in the assessment calculations is to determine the natural phenomena and man-caused events which are potential mechanisms for release of radioactive materials from the repository. One radionuclide at a time is routed through AMRAW-A. The Release Model (see Figure 4-2) provides transfer coefficients which denote the fraction of the repository inventory which is released during each time increment; this becomes input to the Environmental Model. Environmental pathway analysis in the Environmental Model, described in the next section, uses input concentrations in four "receptors": air, land surface, surface water, and ground water. It is convenient for calculation purposes to consider the releases from the geologic formation during an interval of time to four corresponding "preliminary environmental input receptors," (Figure 4-3). Release to air represents the initial ejection into an air suspension. Release to land surface and surface water is the initial commitment to these areas, and release to ground water is the transfer by leaching into ground water at the point of ground water contact. The "OR" gate symbol in Figure 4-3 indicates that any one or any combination of inputs constitutes a release from the repository. More specifically then the Release Model provides values for transfer coefficients to each of the four preliminary environmental input receptors. These preliminary receptors should be visualized as being in the close vicinity of the repository as a step toward subsequent calculation of dispersion to the various geographic zones in the study region.

Careful siting of a waste repository initially provides isolation from circulating ground water and chooses a region with predicted long-term stability to avoid disruptive changes. There are geologic processes which can occur to disrupt a repository and lead to transport of waste inventories, denuding of deposits, or exposure of deposits to ground water. Gera and Jacobs [Ge72] considered the following categories: 1) catastrophic events, including meteorite impact and volcanism, 2) slow geologic processes, including faulting, erosion, glaciation and leaching (followed by ground water transport), and 3) plastic deformation of the disposal formation by salt or shale diapirism. Man-induced processes include accidental or deliberate penetration by drill holes

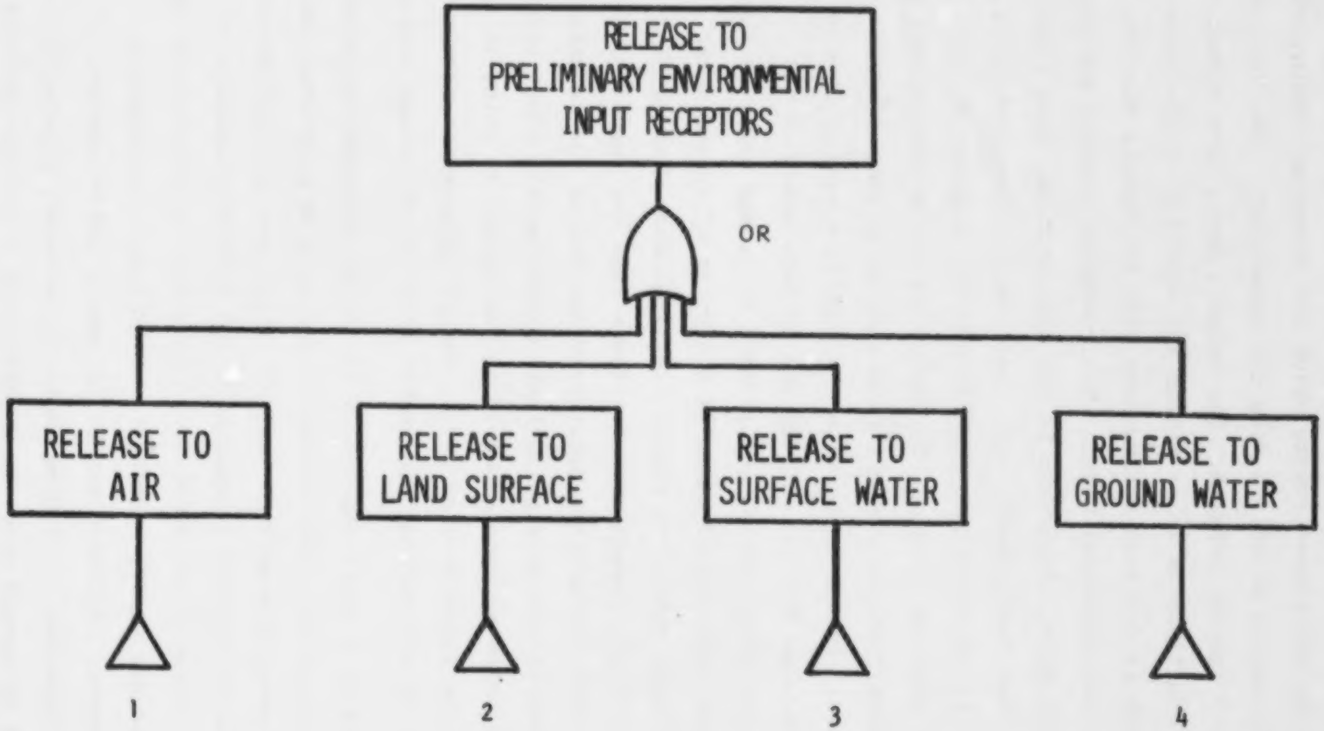


Figure 4-3. Releases from geosphere to preliminary environmental input receptors.

which provide ground water access, failure of shaft seals left after repository operations, and thermal response to waste emplacement.

The transfer coefficient as a function of time to a given preliminary environmental input receptor for a given release mechanism and radionuclide may be defined as

$$A(t) = P(t)\ Al(t),\ y^{-1}. \tag{4-2}$$

Multiplication of this coefficient by the length of a time increment considered gives the fraction of radionuclide inventory which is transferred during the time increment. As explained in subsequent paragraphs, there is a flexible interpretation of the two factors in Eq. 4-2, depending upon the release scenario. Al(t) generally is the fraction of inventory transferred if a release occurs. This is the sudden transfer by a rapid event (specified by input data) or the accumulated transfer during the time increment of interest by a slow event such as leaching into ground water (calculated within AMRAW). P(t) is the annual probability of occurrence of release and is expressed as

$$P(t) = P_1(t) P_2(t) \cdots P_n(t). \tag{4-3}$$

To provide flexibility, each component factor of P(t), treated as being statistically independent, may be any of five functions:

1) Constant: $P_n(t) = C$. Most presently available data on prediction of geologic events are accommodated by this simple representation.

2) Step Function: $P_n(t) = C$ if $t < t_p$

$$P_n(t) = C + B \quad \text{if } t \geq t_p,$$

where t_p is the time of change by amount B. This function applies, for example, to initiation of continuous leaching following a discrete offset faulting event.

3) Ramp Function: $P_n(t) = C$ if $t < t_p$

$$P_n(t) = C + B(t - t_p) \quad \text{if } t \geq t_p$$

where t_p is the time of start of change and B for this function is the slope. This function or the exponential function (described next) is useful for a gradual process such as erosion which has a most probable rate and therefore a most probable time until exposure (and hence release via weathering) but also has decreasing probability of exposure earlier by higher rates of erosion.

4) Exponential Function: $P_n(t) = C \text{ if } t < t_p$

$$P_n(t) = C + \exp[B(t - t_p)] \quad \text{if } t \geq t_p$$

where t_p is the time of start of change with exponential constant B.

5) Delta Function: $P_n(t) = 0 \text{ for } t < t_p$

$$\text{and } t > t_p$$

$$P_n(t) = 1/\Delta t \quad \text{for } t = t_p$$

where t_p is the time of occurrence of a discrete event and Δt is the time increment within which t_p lies. Subsequent multiplication by Δt then generates a unity probability during the increment. This function applies to discrete events.

Input data used by the Release Model in AMRAW consists of the following for each of the four receptors: 1) the number of release events or event combinations (currently dimensioned for up to nine events), 2) the number of factors $P_n(t)$ comprising $P(t)$, specified for each event (currently dimensioned for up to four factors), 3) specification of the function type and corresponding values of parameters C, B, and t_p for each factor and 4) release fraction Al(t) for each event. For release by leaching into ground water, an input value for Al(t) is overridden by a time- and nuclide-dependent value calculated by an AMRAW function subprogram (DLEACH).

1. Release Scenarios. The structure of the Release Model provides for making AMRAW computer runs for several release scenarios: 1) probabilistic distribution of events over time, 2) discrete event at specified

time, 3) several events each at mean time of first occurrence, or 4) dynamic repository simulation. In addition, combinations of these can be accommodated. Available geologic data at the present time provides for only the first two of these scenarios.

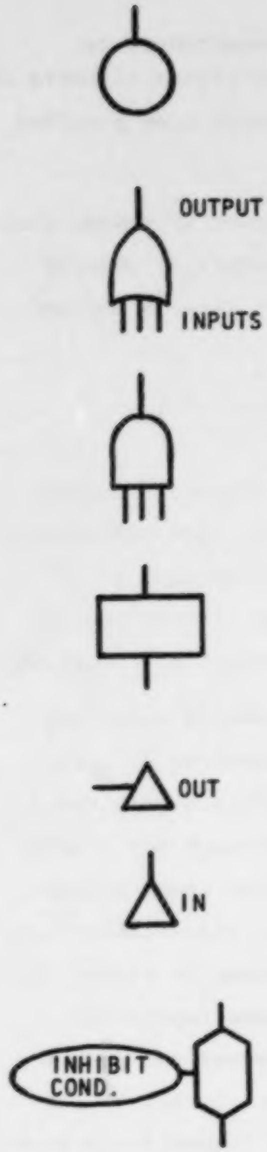
(a) Probabilistic Distribution. Running AMRAW in a mode with potential release events spread out over time by probability density functions provides a measure of long-term risk, where risk is defined as

$$\text{Risk} = \begin{pmatrix}\text{Probability of}\\ \text{Occurrence}\end{pmatrix} \times \begin{pmatrix}\text{Consequences of}\\ \text{Occurrence}\end{pmatrix}.$$

This mode accrues components of risk from a variety of events during each time increment over the range of time considered. Low probability events, though not likely to occur within a study period such as 10^6 years, are given weighted consideration in evaluation of risk and provide for relative comparisons of various waste management alternatives.

Systematic analysis of geologic and man-caused events which may combine in various ways to result in release of radioactive material from a waste repository is necessary. Fault tree analysis provides a systematic method for organizing AMRAW input data, through any technique which combines events into sets may be used. Symbolism used in fault trees is shown in Figure 4 - 4. A simple fault tree, illustrating how probabilities combine at AND gates and OR gates is shown in Figure 4-5 Each path through a fault tree which leads to a release represents a set of conditions existing at a given time which together can permit a release to occur. Each such path comprises a "cut set." All of the cut sets in a simple fault tree can be identified by inspection. Each cut set can be represented by a series of probability factors. For example, one cut set in Figure 4-5 consists of the right hand input to gate B_1 and, say, the middle input to gate B_2, resulting in outputs of the OR gates B_1 and B_2, satisfying the AND gate A_1 causing output of the top event. The overall probability for the cut set can be expressed by $X_1 \cdot X_2 \cdot X_3$, or if preferred $A_2 \cdot X_3$.

Fault tree analysis usually considers a constant probability for each gate input. In this study, the method has been extended with a capability to represent each factor in a cut set as a function of time.



System component or basic fault event.

OR GATE This gate is in the failed state if at least *one* of its inputs is in the failed state.

AND GATE This gate is in the failed state only if *all* of its inputs are simultaneously in their failed states.

EVENT DESCRIPTOR. The rectangle is used to describe the event represented by a gate.

TRANSFER SYMBOLS. These symbols are used to transfer an entire part of the tree to other locations on the tree.

INHIBIT CASE. This represents an event which occurs with some fixed probability of occurrence. The inhibit gate is in the failed state only if its inputs are in the failed state and the inhibit condition has occurred. It is a special type of AND gate.

Figure 4-4. Fault tree symbolism.

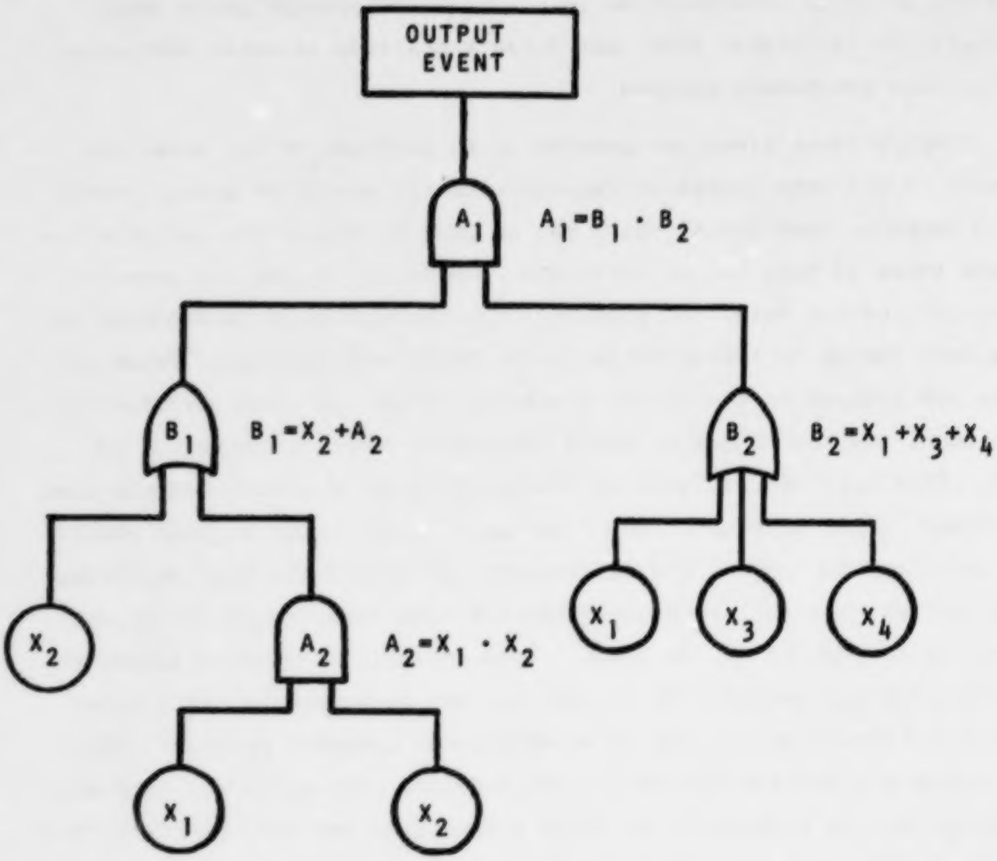


Figure 4-5. Simple fault tree.

The overall probability of each cut set is P(t) with component factors $P_n(t)$, previously described. Fault trees prepared for a demonstration application of AMRAW are presented in detail in Volume II of this report and were presented at a geologic modeling workshop at Ispra, Italy in May, 1977 [Lo77]. The present status of available geologic data results in large uncertainties in estimates of probabilities which affects the calculated risk, but doesn't preclude relative evaluation of various management options.

Complex fault trees can involve up to hundreds of cut sets; the number of cut sets increases rapidly with the use of OR gates. MOCUS is a computer code [Fu74] which may be used to obtain the cut sets for fault trees if they are of sufficient complexity to require computer selection of cut sets. It possesses the capability of determining the cut sets for up to twenty gates in the fault tree per run. These cut sets are grouped in the output according to the top gate specified in the input and the number of input components which comprise the cut set. This type of code reduces the possibility of errors and the time consumed in the determination of cut sets. The output is also easier to interpret for anyone who is not familiar with fault tree analysis. The cut sets and failure probability for each input event of the cut sets may be punched out on cards. This capability of MOCUS allows the overall failure probability of each cut set to be subsequently determined and ranked by the use of an additional computer program. This procedure may provide the ability to consider only those cut sets with overall failure probabilities above a specified cut-off value. In this study, fault trees are simple enough to reduce by visual inspection and the use of MOCUS is not required.

(b) Discrete Events. Running AMRAW in a mode with discrete release events forced to occur at specific times provides for analysis of event consequences. Calculated results must subsequently be weighted by judgment which considers the probability of each such event actually occurring. This mode does not require estimates of probabilities, but fault trees serve as a convenient display of event relationships and assist in selecting events or combinations of events to be considered in consequence analysis. The probability function input

provisions in AMRAW provide for specifying discrete events. A rapid event occurring at a specific time is simply input as a delta function plus the corresponding release fraction A1. Repeated occurrences are handled by additional pseudo cut sets, each with the appropriate delta function. An offset faulting event which initiates exposure to ground water and results in leaching is input as the appropriate step function, assuming that once initiated the leach incident continues until a given radionuclide is depleted by decay and/or leaching removal. If rock mechanics studies indicate that a fracture should be considered as closing up or healing after some time elapses, this is handled by another factor with reverse step function to "turn off" the leach incident at the appropriate time.

(c) Statistical Mean-Time Occurrence. A possible mode of operation of AMRAW is to estimate the mean time to first occurrence for each postulated event by statistical analysis and then input each of these as discrete events at appropriate times. No work has been done on this approach during this study; it is expected that more geological research is first needed.

(d) Dynamic Repository Simulation. This involves geologic modeling of tectonic movements, rock mechanics and waste/rock interactions, to represent the gradual geologic processes and thermal effects of waste emplacement. Work on such modeling is beyond the scope of this study but was started recently at Battelle Pacific-Northwest Laboratories and at Sandia Laboratories. Preliminary concepts were presented by Burkholder (Battelle) and Tierney (Sandia) at the Ispra, Italy geologic modeling workshop in May, 1977 [OECD77, Bu77].

It may take another year before results from dynamic modeling are ready for input to assessment models, but the flexibility of the AMRAW Release Model provides for dynamic input now. It is visualized here that the results of a large effort in dynamic simulation will produce a graph of release rate, perhaps in Ci/y, versus time. There can be such a graph for release to each environmental receptor, and for different radionuclides. The graph can be restated as fraction of instantaneous repository inventory released per year. Figure 4-6 arbitrarily illustrates a possible graph in which no release is expected until some future time when small releases occur followed by increasingly disruptive events. This can be input to AMRAW as one "cut set"

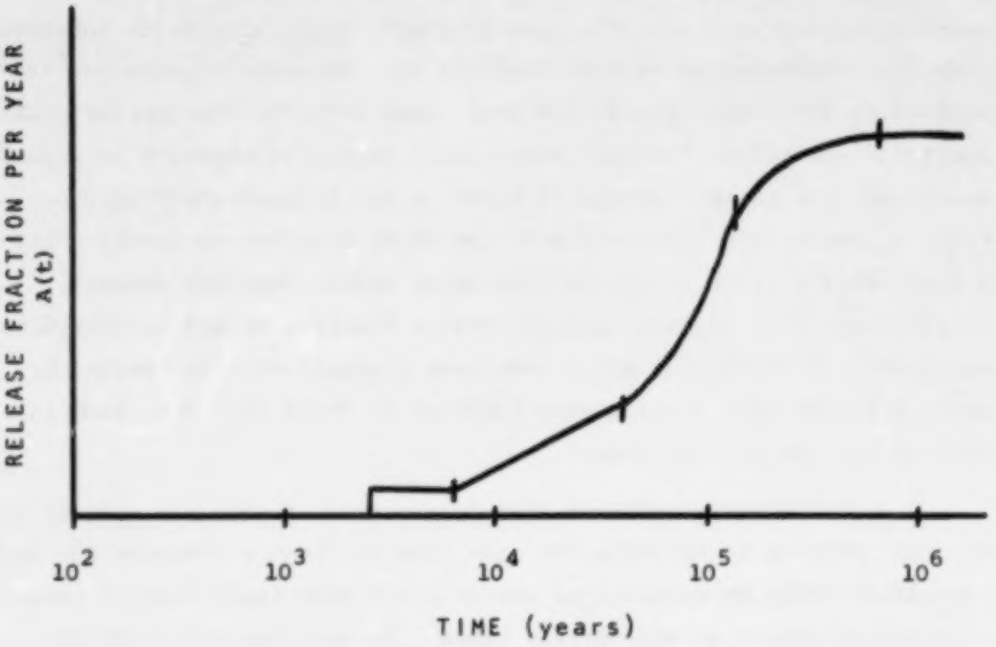


Figure 4-6. Conceptual dynamic repository simulation response.

with a sequence of step, ramp, and exponential factors represented by factors $P_n(t)$ described earlier. An alternate is to break the curve into two or more additive components. Each of these components can then become a separate cut set with appropriate defining factors.

(e) Example of Release Model Calculations. As an example of the calculation through the Release Model, consider data from the probabilistic mode presented in Volume II and release of Sr-90 to air as a result of a volcanic explosion sometime during the time interval 400 - 500 years (after start of repository operations). AMRAW calculates the average inventory during a time increment as the arithmetic average at the beginning and end of the increment as illustrated by the example. This is considered to be more valid than using inventories at the ends of the time increments. The average inventory of Sr-90 at risk comes from the source term for times of 400 and 500 years: $(7.82 \times 10^3 + 7.85 \times 10^2)/2 = 4.30 \times 10^3$g. Multiplying by specific activity, 1.42×10^2 Ci/g obtains 6.11×10^5 Ci. The Release Model obtains from data input for the volcanic explosion cut set: one factor, a constant, for $P(t) = 2.4 \times 10^{-12}$, and the expected value of release fraction $A1(t) = 0.075$.

The release transfer coefficient becomes

$$A(t) = P(t)Al(t) = (2.4 \times 10^{-12})(0.075)$$

$$= 1.8 \times 10^{-13}, y^{-1}$$

and the release going to the air preliminary environmental input receptor is

$$(6.11 \times 10^{5}Ci)(1.8 \times 10^{-13}/y)(100y) = 1.1 \times 10^{-5}Ci .$$

2. Release Barriers. A multi-barrier concept is applied in a geologic isolation repository to prevent or impede release to and transport through the geosphere to the biosphere. Each of these is reviewed briefly in the following paragraphs.

(a) Geologic Structure. A site for geologic isolation of radioactive waste is chosen to provide a stable geologic formation with host rock free of circulating ground waters. In AMRAW, potential disruptions are considered which could change the initial conditions and exhume waste material or allow ground water to reach the repository zone.

(b) Container. Most of the waste emplacement methods under consideration utilize a sealed metal canister to contain a solidified form of the waste. For rock-melting concepts, the canister is sacrificial and is only a temporary barrier. For non-melting concepts, the canister provides a barrier for up to tens of years. In AMRAW, this container is neglected for terminal storage analysis for which a geological time frame is involved.

(c) Leach Resistance. A major barrier to release of nuclides into the geosphere is the use of a leach resistant solidified form of waste, such as glass. Leaching occurs only if events occur which permit ground water to come into contact with emplaced waste. The next section of this chapter describes the calculation of leach rates in an AMRAW subroutine.

(d) Nuclide Retention by Sorption. If release to the geosphere by leaching occurs, entry to environmental input receptors requires transport via ground water movement to the biosphere. During the

migration, sorption processes such as: adsorption, ion exchange, colloid filtration, reversible precipitation, and irreversible mineralization occur, retarding nuclide movement. The ground water transport model is in the Transport-to-Environment portion of the Environmental Model, described later in this chapter (Section D.1.).

3. Leaching in Ground Water. Leaching of a waste deposit followed by transport in aqueous solution is an important process that occurs prominently in the Release Model and subsequent Environmental Model particularly for an underground repository storage. The calculation of leach rates in an AMRAW subroutine applies the leaching model presented in following paragraphs.

Many studies on the incorporation of the radioactive waste in solid media [Br74, Gd69, Me73, Me72, Ra72, Sm69] have included the effect of time on leaching. The time law expression [Aℓ61, Lu70, We67]

$$L = \alpha t^{1/2} + \beta t \qquad (4\text{-}4)$$

which was developed from studies on the leachability of commercial glasses by aqueous solutions [Gv66, Me73] has been used to characterize the cumulative amount, L, of the radioactive isotope leached from the solidified waste for a specified leach period. Here, it is assumed that the glass matrix does not undergo devitrification. In Eq. 4-4 α and β are empirical constants and t is time.

Equation 4-4 shows that the amount leached follows a parabolic relationship with time at short times and approaches linear kinetics at longer times. Differentiation of Eq. 4-4 with respect to time yields

$$\frac{dL}{dt} = \left(\frac{\alpha}{2}\right) t^{-1/2} + \beta \qquad (4\text{-}5)$$

which shows that the rate of leaching varies with the reciprocal of the square-root of time at short times and becomes constant at long times.

It must be pointed out that an accurate evaluation of Eq. 4-4 will require experimental leaching tests to determine the constants α and β [Gd74, We67, Aℓ61, Lu70]. However, experimental tests may not be available in measuring α and β for a specific leach process, in which case an approximation for L may be employed. For example, various leaching investigations have made use of Fick's laws of diffusion [Bℓ72, Br74, Gd69, Gd74, Gf74, Me73, Ra72, Rt73a, Sm69] as a means of estimating L. Consequently, the diffusional transport model by Godbee and Joy [Gd74], which considers Fickian diffusion with a concentration-dependent dissolution rate for sparingly-soluble species, has been employed in this analysis to describe the amount of radioactive species leaving the solid waste matrix.

The governing equation and the accompanying limiting conditions as developed by Godbee and Joy [Am72, Gd74] for the diffusion of radioactivity from the semi-infinite solid waste are given by

$$\frac{\partial C}{\partial t} = \mathcal{D}_e \frac{\partial^2 C}{\partial x^2} + k(C_s - C) \qquad (4-6)$$

$$C = C_s \qquad t = 0,\ x > 0 \qquad (4-6a)$$

$$C = 0 \qquad t > 0,\ x = 0 \qquad (4-6b)$$

$$C = C_s \qquad t > 0,\ x = \infty \qquad (4-6c)$$

where C is the concentration of the mobile species at any time t and space x, $\mathcal{D}_e$ is the effective diffusivity for the species, k is a dissolution rate constant, and C_s is the uniform initial concentration of mobile species. The initial concentration of mobile forms of a species (C_s) may be assumed to be at saturation for these forms in the matrix. In addition, the rate of transformation of less mobile forms of the species to more mobile forms can be taken as linearly related to the concentration driving force ($C_s - C$) which is the difference between the saturation concentration and the average concentration of mobile species at any time. The rate referred to is the second term on the right side of Eq. 4 - 6. The dissolution rate of the waste matrix itself is also assumed to be low compared to the migration rate of species to the matrix surface, so that essentially there is no moving boundary.

Equation 4 - 6 does not consider radioactive decay which takes place in competition with the diffusion process and also occurs in the leachant. Leaching during an increment of time is determined on a basis of the average inventory of a particular radionuclide as listed in the source term. Following leaching, a decay factor is applied to account for radioactive decay. Evaluation of the factor (DECFAC) and its application are described in Section D.1. of this chapter.

A method of solution [Da70, Gd74] of Eq. 4 -6 involves the introduction of a transformation variable

$$\eta(x,t) = C_s - C(x,t) \tag{4-7}$$

into Eqs. 4 - 6 to 4 - 6c to yield the following corresponding expressions

$$\frac{\partial \eta}{\partial t} = \mathcal{D}_e \frac{\partial^2 \eta}{\partial x^2} - k\eta \tag{4-8}$$

$$\eta = 0 \qquad t = 0,\ x > 0 \tag{4-8a}$$

$$\eta = C_s \qquad t > 0,\ x = 0 \tag{4-8b}$$

$$\eta = 0 \qquad t > 0,\ x = \infty\ . \tag{4-8c}$$

Equations 4 - 8 to 4 - 8c may be solved analytically [Da70], yielding

$$\eta = \frac{C_s}{2}\left\{\exp\left[-x\left(\frac{k}{\mathcal{D}_e}\right)^{1/2}\right]\operatorname{erfc}\left[\frac{x}{2(\mathcal{D}_e t)^{1/2}} - (kt)^{1/2}\right]\right.$$

$$\left. + \exp\left[x\left(\frac{k}{\mathcal{D}_e}\right)^{1/2}\right]\operatorname{erfc}\left[\frac{x}{2(\mathcal{D}_e t)^{1/2}} + (kt)^{1/2}\right]\right\} \tag{4-9}$$

where erfc y = 1 - erf y

$$\operatorname{erf} y = \frac{2}{\sqrt{\pi}}\int_0^y e^{-z^2}\,dz.$$

The error function (erf) is a monotone increasing function ranging from 0 to 1. Properties and tabulated values of the error function and complementary function (erfc) can be found in texts and handbooks of mathematics [Ab70, Kr67].

(a) Predictor Equation for Leaching. Direct substitution of Eq. 4 - 9 into Eq. 4 - 7 gives the concentration of the mobile species in the medium as a function of time and space, which is

$$C = C_s \left\{ 1 - \frac{1}{2} \exp\left[- x \left(\frac{k}{\mathcal{D}_e} \right)^{1/2} \right] \operatorname{erfc} \left[\frac{x}{2(\mathcal{D}_e t)^{1/2}} - (kt)^{1/2} \right] \right.$$

$$\left. - \frac{1}{2} \exp\left[x \left(\frac{k}{\mathcal{D}_e} \right)^{1/2} \right] \operatorname{erfc} \left[\frac{x}{2(\mathcal{D}_e t)^{1/2}} + (kt)^{1/2} \right] \right\} . \qquad (4\text{-}10)$$

The rate at which the radioactive species diffuses into the leaching can be obtained by computing the flux J(t) across the interface, i.e. at $x = 0$. Thus, from Fick's first law [Js60]

$$J(t) = - \mathcal{D}_e \left. \frac{\partial C}{\partial x} \right|_{x = 0} \qquad (4\text{-}11)$$

the total amount of activity accumulated in the leachant over a period of time is then equal to the time integral of the flux, i.e.

$$\sum^{n} a_n = F_s \int_{0}^{t} J(t)\,dt \qquad (4\text{-}12)$$

where a_n is the incremental amount leached for n leach period renewals. (Note: each time increment in AMRAW is divided into n subdivisions for leaching calculations.)

Differentiating Eq. 4-10 with respect to x, evaluation of the gradient at $x = 0$, inserting into Fick's Law, Eq. 4-11, and integrating over time, Eq. 4-10 eventually leads to the following resultant expression

$$L_p = \frac{F_s}{V_s} A_o (\mathcal{D}_e k)^{1/2} \left[\left(t + \frac{1}{2k} \right) \operatorname{erf} (kt)^{1/2} + \left(\frac{t}{\pi k} \right)^{1/2} e^{-kt} \right] \qquad (4\text{-}13)$$

where $L_p = \sum^{n} a_n$. The parameter F_s is the total exposed area of specimen, V_s is the specimen volume, and A_o is the initial total radioactivity of the species subject to leaching. To obtain the corresponding fraction, ξ, of the initial amount leached, L_p in Eq. 4-13 is divided by A_o, i.e.

$$\xi = \frac{L_p}{A_o} = \frac{F_s}{V_s}\,(\mathcal{D}_e k)^{1/2}\left[\left(t + \frac{1}{2k}\right)\mathrm{erf}\;(kt)^{1/2} + \left(\frac{t}{\pi k}\right)^{1/2} e^{-kt}\right]. \tag{4-14}$$

Equation 4 - 13 is thus the predictor equation for the amount of radioactive species leached from the solidified waste for a specified leach period (L in Eq. 4 -4). It should again be pointed out that radioactive decay is applied subsequently by use of a decay factor. Godbee and Joy [Gd74] interpret the application of Eq. 4-13 to that of a "stable isotope."

It is important to examine Eq. 4 - 13 to determine whether its behavior is consistent with that predicted by Eq. 4 - 4 . At short times, Eq. 4 - 13 becomes [Da70, Gd74]

$$L_p \approx 2\,\frac{F_s}{V_s}\,A_o\left(\frac{\mathcal{D}_e}{\pi}\right)^{1/2}\left[\left(1 + \frac{1}{2}\,kt\right)\,t^{1/2}\right] \tag{4-15}$$

which, for small kt, follows a parabolic relationship as in Eq. 4-4. For very long times, erf $(kt)^{1/2}$ approaches unity and Eq. 4-13 becomes [Da70, Gd74]

$$L_p \approx \frac{F_s}{V_s}\,A_o(\mathcal{D}_e k)^{1/2}\left(t + \frac{1}{2k}\right) \tag{4-16}$$

for the amount leached. As was observed in Eq. 4 - 4 the above equation (4 - 16) also follows a linear relationship with time. Much of the available results from work on the leaching of glasses [Rt73b, Sm69], especially silicates, reveal that the total amount leached varies with the square-root of time at short times and approaches a linear relation at longer times. This is the behavior predicted by Eq. 4-13.

Differentiation of Eq. 4 - 15 with respect to time when kt is very small yields

$$\frac{dL_p}{dt} \approx \frac{F_s}{V_s}\,A_o\left(\frac{\mathcal{D}_e}{\pi}\right)^{1/2} t^{-1/2} \tag{4-17}$$

and the differentiation of Eq. 4 - 16 with time correspondingly yields

$$\frac{dL_p}{dt} \approx \frac{F_s}{V_s} A_o (\mathcal{D}_e k)^{1/2} \tag{4-18}$$

For short times Eq. 4 - 17 predicts the leach rate as a function of the reciprocal of the square-root of time; Eq. 4 - 18 predicts a constant leach rate at long times. Both cases are consistent with the predictions of Eq. 4 - 4.

The use of the effective diffusivity $\mathcal{D}_e$ as it is applied in Eq. 4 - 6 is appropriate since it is implicitly assumed that the diffusion of the species from the solidified waste can be characterized by small concentration changes on the diffusing species, in which case Fickian diffusion is the controlling mechanism, and $\mathcal{D}_e$ can henceforth be assumed to be independent of time, position, and concentration.

In this analysis $\mathcal{D}_e$ is estimated using Eq. 4 - 23, discussed in the following section. Subsequently the estimated $\mathcal{D}_e$ is utilized in determining the dissolution rate constant k by iteration via a curve-fitting procedure. The value of k is adjusted until the theoretically predicted profile (e.g., L_p vs. t plot of Eq. 4 - 13) adequately coincides with experimentally measured leach data [Gd74]. Leach data from phosphate-glass by Mendel and McElroy [Gd74, Me72] is used in this iteration procedure. Comparison plots of the experimental amounts of Cs-137 leached and those predicted by Eq. 4 - 13 from a phosphate-glass product and a cement-sludge matrix are presented by Godbee and Joy [Gd74]; agreement is very good.

(b) Estimation of Diffusivity. The kinetic theory of liquids is not as developed as for gases, where the kinetic theory of gases is well-known [Da70, Pe63, Pr58]. It is not surprising, therefore, that there are no satisfactory methods of predicting diffusivities in liquid systems from first principles. Diffusivity coefficients in liquids are about four orders of magnitude smaller than in gases and are more difficult to measure [Pe63].

Estimation of the diffusivity coefficients is done with the use of the Stokes-Einstein relation [Bi60], given by

$$\mathcal{D}_e = KT \frac{1}{6\pi\mu R_k} \tag{4-19}$$

where K is the Stokes-Einstein constant equal to 1.38×10^{-16} g cm^2/sec^2 molecule °K; μ is the solvent viscosity at absolute temperature T °K (2.35×10^{-3} g/cm sec at 523°K for water); and R_k is the radius of the diffusing particle in cm. Eq. 4 - 19 considers the diffusing particle to be spherical in shape and also assumes that the solvent, here taken as water, appears to the diffusing species as a continuum [Bi60]. Using an average temperature of 250°C (523°K), Eq. 4 - 19 simplifies to

$$\mathcal{D}_e = \frac{1.885 \times 10^{-17}}{R_k} \quad \frac{\text{cm}^2}{\text{d}} . \qquad (4\text{-}20)$$

The radius R_k of the diffusing species is approximated using the Loschmidt method. Present [Pr58] adequately describes this method, which assumes that the molar volume in the solid state (M/ρ) is of the order of magnitude of $N_A(2R_k)^3$, i.e.

$$N_A(2R_k)^3 \simeq \frac{M}{\rho} \qquad (4\text{-}21)$$

where N_A is Avogadro's number ($6.025 \times 10^{23} \frac{\text{molecules}}{\text{g mole}}$); M is the molecular weight of the diffusing species; and ρ is the mass density in the solid state in g/cm^3. Eq. 4 - 21 simplifies to

$$R_k \simeq 5.92 \times 10^{-9} \sqrt[3]{\frac{M}{\rho}} \quad \text{cm} \qquad (4\text{-}22)$$

which is combined with Eq. 4 - 20 to yield

$$\mathcal{D}_e \simeq 3.18 \times 10^{-9} \sqrt[3]{\frac{\rho}{M}} \quad \frac{\text{cm}^2}{\text{d}} . \qquad (4\text{-}23)$$

It should be pointed out that Eq. 4 - 23 provides merely a rough approximation for the diffusivity coefficient. The Wilke-Chang semi-empirical equation [Sk74], given by

$$\mathcal{D}_e = 6.39 \times 10^{-3} \frac{T(X\, M_s)^{1/2}}{\mu\, \bar{V}^{0.6}} \quad \frac{\text{cm}^2}{\text{d}} \qquad (4\text{-}24)$$

is a better relation to use where the solvent is water. Here, T and μ are defined as before (except that μ will have units of centipoise),

M_s is the molecular weight of the solvent, $\tilde{V}$ is the molecular volume of the solute at the normal boiling point in cm^3/g mole, and χ is an "association" parameter. The association parameter χ refers to the solvent and is 2.6 for water [Da70]. However, there is apparent rigor in employing Eq. 4 - 24, particularly where it is applied beyond simple substances. For example, in estimating $\tilde{V}$, the contributions of the atoms in the molecule are added up in the case of complex substances, and are subtracted in the case of ring-compounds [Da70]. Specific details of waste form and chemical composition are beyond the scope of this study, necessitating use of the Stokes-Einstein approximation for determining effective diffusivity $\mathcal{D}_e$ instead of the more accurate Wilke-Chang equation.

(c) Example of Leaching Calculations. An offset fault which results in ground water coming in contact with a portion of the canisters in the repository inventory constitutes a leach incident. AMRAW calculates the amount leached during a given release time increment and obtains the corresponding release fraction $A\,l(t)$. An example is presented here to illustrate the steps. Consider a leach incident during the time increment 900 - 1000 years (after beginning of repository operations), and consider release of C-14 by leaching. The average inventory of C-14 corresponding to these times, obtained from the source term, is $(3.64 \times 10^4 + 3.59 \times 10^4)/2 = 3.62 \times 10^4$g. This is multiplied by its specific activity, 4.45 Ci/g, to yield the radioactivity, i.e.

$$(3.62 \times 10^4)(4.45) = 1.61 \times 10^5 \text{ Ci.}$$

If this activity is evenly distributed in a total canister inventory of 62,500 canisters but only one row of 250 canisters is subject to leaching at a time (both values are input to AMRAW), then the C-14 exposed to leaching, A_o, is $1.61 \times 10^5(250/62{,}500) = 6.44 \times 10^2$ Ci. Section 6.B, Vol. II, describes the canister dimensions, where the total surface area per canister exposed, F_s, is 4.38×10^4 cm^2 (this value assumes that the canister disintegrates into ten parts) and the specimen volume per canister, V_s, is 2.22×10^5 cm^3 (both values are input to AMRAW).

Proctor [Pc66] describes a typical composition of radioactive wastes from the reprocessing of spent reactor fuel. If, for example, C-14 is present in the solidified waste matrix as carbonate, for calcium carbonate M = 100 and ρ = 2.71 g/cm^3 [Pe63] can be substituted in Eq. 4-23 to approximate $\mathcal{D}_e$. Thus, from Eq. 4-23

$$\mathcal{D}_e = 3.18 \times 10^{-9} \sqrt[3]{\frac{2.71}{100}} = 9.55 \times 10^{-10} \frac{\text{cm}^2}{\text{d}} .$$

This estimated $\mathcal{D}_e$ is used to determine the dissolution rate constant k as described in Section 4.C.3, and is found to be 4.96 x 10^{-3}/d. This determination of $\mathcal{D}_e$ and k is done externally to AMRAW and the values are furnished as input data. Finally, use of Eq. 4 - 16 yields the predicted activity of C-14 leached during the time interval, t = 100 x 365 days:

$$\frac{4.38 \times 10^4}{2.22 \times 10^5} (6.44 \times 10^2) \sqrt{(9.55 \times 10^{-10})\ (4.96 \times 10^{-3})}$$

$$\times \left[100 \times 365 + \frac{1}{2} \frac{1}{4.96 \times 10^{-3}} \right] = 10.1 \text{ Ci}.$$

This is the activity leached into the ground water preliminary input receptor during the time increment of interest.

As performed within AMRAW, the calculation sequence is rearranged for programming convenience as follows:

1) Calculate mass leach rate, gm/cm^2-d, in a subprogram (RLEACH).

2) Multiply by the areas exposed to leaching, F_s, and, by the time interval, t = 100 x 365 d, obtaining grams leached during intervals.

3) Divide by average inventory during interval (grams), obtaining dimensionless release fraction, A1(t). This value, calculated as grams released per gram inventory, also represents Ci released per Ci inventory.

4) Multiply by annual probability of leach incident, P(t), obtaining the transfer coefficient, A(t).

5) Multiply A(t) by average inventory (1.61 x 10^5 Ci) and by time

increment, t, (100 y), obtaining the release to the ground water receptor.

The calculation may consider either a discrete leaching event commencing at a specified time or may be distributed probabilistically. For a given time increment, t, an input probability of 1/t when multiplied by duration t generates a unity probability for occurrence. Therefore, if the probability is 1/t, a leach incident occurs (or continues) and the amount released becomes the 10.1 Ci calculated above. In a probabilistic mode where P(t) is the probability of offset faulting (such as $1.4 \times 10^{-7}\ y^{-1}$), the release on a probabilistic basis is correspondingly less.

More specifically, the calculation in AMRAW divides a given release time increment into 10 sub-intervals (5 if increment is 100 years or less), and calculates the average of leach rates obtained for each sub-interval).

4. Model Output. In summary, the Release Model in AMRAW provides values of transfer coefficients used by AMRAW, for each radionuclide in turn, to generate a matrix (denoted by the computer variable RlJ) of releases in Curies to each of the four preliminary environmental input receptors (air, land surface, surface water, and ground water), during each of the time increments considered. Subsequent transport to environmental receptors in each geographic zone, adjustments for decay processes and accumulations for all release increments is handled by the Environmental Model.

D. ENVIRONMENTAL MODEL

The Environmental Model is divided into two parts: 1) Transport to Environment, and 2) Environment to Man Pathways. The first part uses releases to the four preliminary environmental input receptors from the Release Model output matrix and calculates the corresponding concentrations in the environmental input receptors for each of the geographic zones. The second part of the Environmental Model performs the pathway analysis and calculates dose to man.

1. Transport to Environment. The Release Model calculates quantities of each radionuclide, in Curies, released during each time interval (by probabilistic, discrete event, or other modes). The releases are initially collected in Preliminary Environmental Input Receptors (Fig. 4 - 7) representing four categories of environmental input: air, land surface, surface water, and ground water. Several steps are required to calculate environmental receptor net concentrations for the subsequent pathway analysis. These steps are summarized as follows and then discussed in detail:

1) Calculate dispersion of the release increment to the several geographic zones.

2) Adjust for transfers from each receptor to the other three receptors.

3) Calculate average concentrations for the activity remaining in each receptor.

4) Calculate residual activity during each time increment subsequent to release.

5) Accumulate concentrations in each time increment from all current or prior releases.

(a) Dispersion to Zones. The first step in obtaining environmental concentrations is to allocate the initial releases to each geographic zone. The relationships for one zone during the time increment coincident with the release time increment are illustrated in Fig. 4 - 8. AMRAW terminology, with subscripts omitted, is shown as labels where this can be helpful in relating this discussion with other material describing

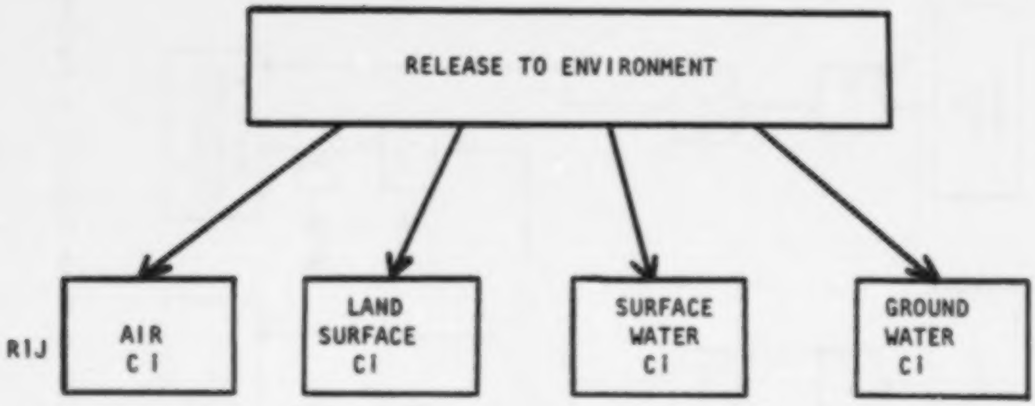


Figure 4 - 7. Preliminary environmental input receptors.

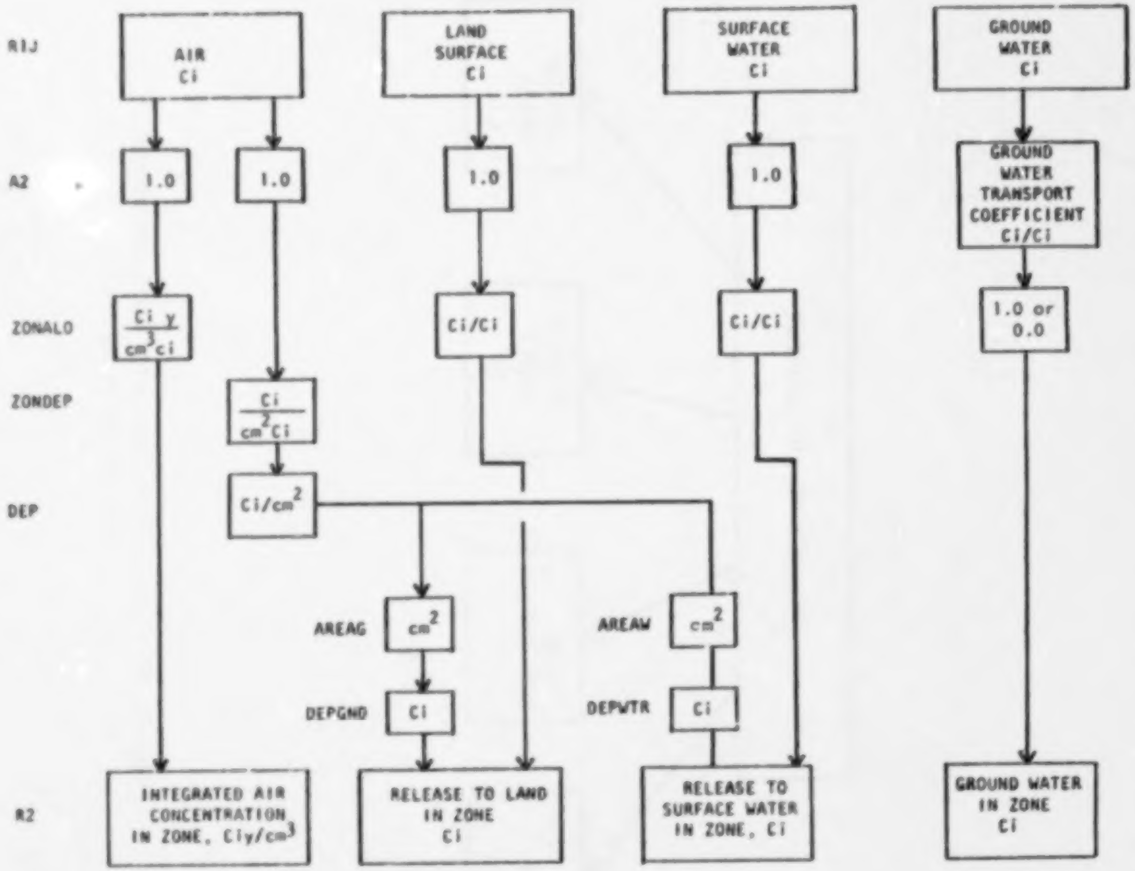


Figure 4-8. Dispersion to a zone during a release time increment.

the code. The first factor, A2, accounts for retardation, radiodecay, and environmental decay effects. Data statements in the program set these values equal to unity for the first three receptors (air, land surface, and surface water) for the environmental time increment which is coincident with the release time increment. For ground water, A2 is evaluated by a ground water transport subroutine (CRATIO), described later.

The dispersion allocation factors, ZONALO, are not calculated within AMRAW but are determined by application of existing dispersion models or codes, considering the effective surface areas of land and water in each zone, and are furnished to AMRAW as input data. First, consider the receptor for air. Any of several codes calculate air concentrations and ground deposition as a function of distance and direction from a release point. For a continuous uniform release rate (in Ci/y), air concentrations, $(\mathrm{Ci/cm}^3)/(\mathrm{Ci/y})$, and ground deposition rates, $(\mathrm{Ci/cm}^2\text{-}\mathrm{y})/(\mathrm{Ci/y})$ can be obtained. The ground deposition rate is approximately equal to air concentration multiplied by an effective deposition velocity but the effects of wet deposition cause some variation from this relationship. If an acute release occurs at some time within a given release time increment and involves activity equal to the integrated chronic release for the release time increment, integrated concentrations result which are numerically equal to the chronic case. Integrated air concentration, $(\mathrm{Ci\text{-}y/cm}^3)/\mathrm{Ci}$, and integrated ground deposition, $(\mathrm{Ci/cm}^2)/\mathrm{Ci}$ can therefore also be obtained. Acute releases are assumed in Fig. 4-8 and in AMRAW programming, but it should be pointed out that the corresponding integrated dose during a time increment is numerically the same whether a release is treated as chronic or acute. The air concentration factor, ZONALO, and ground deposition factor, ZONDEP, in Fig. 4 - 8, are simply the area weighted average values for each zone obtained by an air dispersion code, e.g. [Mo75].

Time increments in AMRAW are generally set to be at least several years. Therefore, air deposition is relatively instantaneous following a release. This is shown in Fig. 4 - 8 as a deposition concentration, DEP, in units of $\mathrm{Ci/cm}^2$. The corresponding deposition on land surface area in the zone, AREAG, is ground deposition DEPGND, in Curies. The deposition on surface water area, AREAW, is DEPWTR, also in Curies.

deposition on surface water area, AREAW, is DEPWTR, also in Curies.

Next consider the receptors for land surface and surface water. In addition to air deposition, the fault tree model includes direct release to land surface and water surface. Mechanisms include ballistic trajectory dispersion from violent events, lava flow, etc. Again, the allocation factors, ZONALO, are determined by external modeling and furnished to AMRAW as input data. Models for this purpose are not well developed and approximations are necessarily used for current AMRAW implementations.

The allocation factor, ZONALO, for the ground water receptor is used as a flag to denote whether or not there is discharge or well water withdrawal in the zone with flow from the repository area. A value of 0.0 indicates a direction of the zone relative to the repository such that contaminated water cannot enter the zone or that other factors preclude such water from entering the biosphere in the zone. A value of 1.0 indicates discharge or use in the zone. In this case, the factor A2 is the ground water transport factor, calculated by a subroutine (CRATIO) for the distance from the repository to the average discharge point in the zone and for the accumulated transport time for the release increment. The ground water transport model is described later in this section.

The initial values of releases after allocation to the zones are represented by R2 in Fig. 4 - 8. At this stage, the inventories are retained in Curies because further adjustments are required before conversion to environmental concentrations.

(b) Interreceptor Adjustment. Simultaneously with the dispersion to the four receptors in each zone, transfers between receptors occur. For example, surface deposits can be partially resuspended into the air, or washed off into surface water, ground water can discharge to surface water, and ground and surface water can be deposited on land surface by irrigation. These and other transfer processes for a given zone are shown in Fig. 4 - 9. Resuspension from surface water and ground water is included in Fig. 4 - 9 as dashed lines; AMRAW checks for input data related to these transfers but they are expected to be noncontributors. Air deposition to surfaces is included in the

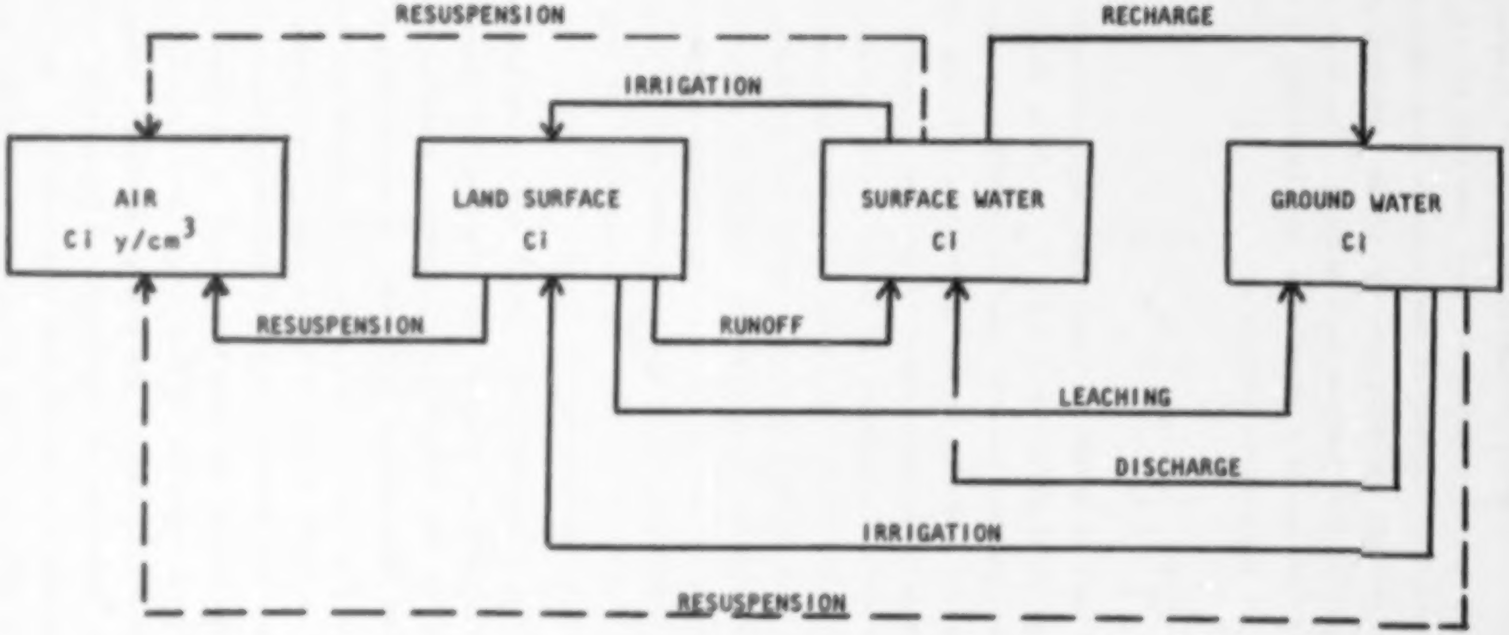


Figure 4 - 9. Adjustments for interreceptor transfers.

dispersion calculations previously discussed and does not require further treatment in the adjustment sequence. Each transfer process is visualized as transferring a fraction of one receptor pool, with calculated radionuclide content, per unit time to another receptor pool; the untransferred balance then becomes more diluted. The fraction of inventory transferred from one pool to another (ADJ in AMRAW) is therefore represented by the exponential expression

$$G_m = E_m \left[1 - \exp(-0.5F_m \, \Delta t)\right] \qquad (4\text{-}25)$$

where E_m (designated ADJ1 in AMRAW) is input data representing the maximum fraction which can be transferred (≤ 1.0), F_m (ADJ2 in AMRAW) is a transfer rate constant, and the average time for transfer of portions of the inventory (average of transfer to the beginning and to the end of the time increment considered) is one-half of the time increment Δt (DELTE in AMRAW). If the rate constant is large, a step transfer $G_m = E_m$ is used. Resuspension into air uses a modified expression (G_m is multiplied by land surface inventory and Δt and divided by land area) to obtain integrated air concentration, consistent with the units for that receptor. In this case, E_m is the resuspension factor. It should be noted that AMRAW uses input constants developed by externally applied models or rationale. The result from exercising this step is the adjusted receptor inventories, R2, in Fig. 4 - 10 .

(c) Convert to Concentrations. After calculating dispersion to zones for each environmental receptor and adjusting for inter-receptor transfers during the release time increment, a simple step is taken to convert the inventories, in Curies, to concentrations in each zone, as shown in Fig. 4-10. The dispersion parameter, DISPN, is land surface area or water volume as appropriate. For ground water, the dilution volume for the leachant is the effective volume of the ground water plume flow during the time increment. It is convenient to convert from Curies to micro-Curies in this step. The concentrations are accumulated in the matrix R2TOT. The pathway analysis, discussed later in this section, makes use of the integrated deposition during each release time increment for terrestrial food products. For this purpose, deposition is retained in the non-accumulated matrix, GNDEP.

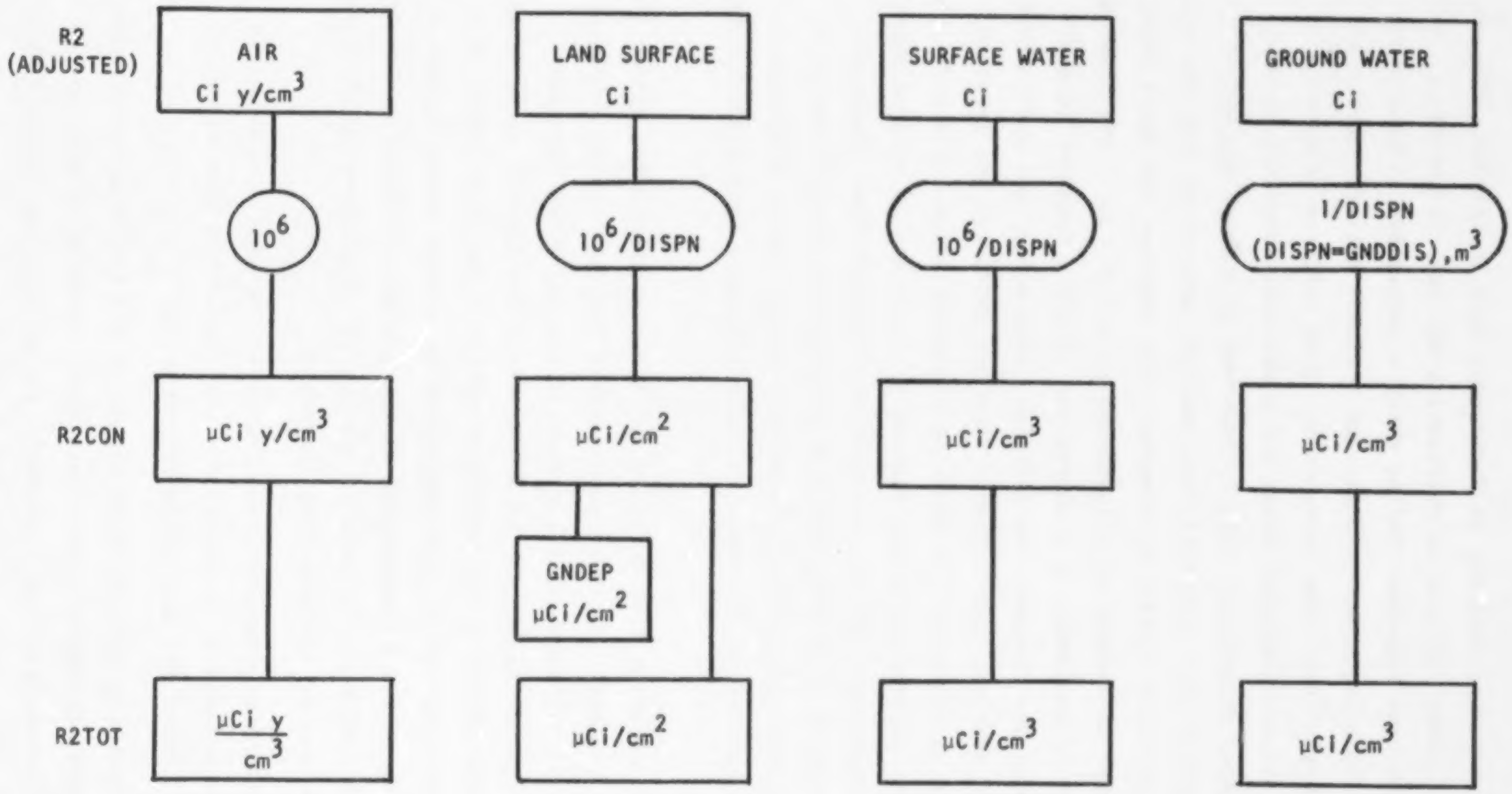


Figure 4 - 10. Conversion of adjusted inventories to concentrations.

(d) Residual Activity in Subsequent Time Increments. The above discussion describes the step in calculating the net concentrations associated with the time increment during which a calculated release occurs. The next step is to determine the average residual activity during all subsequent environmental time increments. This requires accounting for physical and environmental decay and additional transfers between the environmental receptors. This is followed by summing up, within each environmental time increment, the residual activities from the current and all previous release increments. The sequence for doing this between two time increments is illustrated in Fig. 4 - 11 . The transfer coefficient A2 is evaluated in a subroutine (TRINP - Transfer to environmental input) and includes two factors: radiodecay, and environmental decay, applied over the time interval from the middle of the previous time increment to the middle of the time increment being evaluated. The method used for determining these factors is described in the following subsection. There are removal and fixation processes that gradually remove each nuclide from effective environmental movement; these processes lead to the concept of environmental decay. It is difficult to obtain appropriate decay constants to fully implement this provision in the model.

The air suspension from a release is fully accounted for within the release time increment and there is no direct residual during subsequent times (A2 = 0.0, via input of a large environmental decay constant). That is, any release to the air is deposited on the surface or is swept out of the study region by air movements within a few days. This is a very short time compared to time increments of several years or more, and there is therefore no subsequent direct residual. There is, however, a resuspension component fed back to the air by inter-receptor adjustment (land surface to air) for each time increment.

For ground water transport, the factor A2 for each environmental time following release is evaluated for the cumulative time since release. This is detailed in a following subsection.

After accounting for the decay processes and the delay associated with ground water transport, each quantity R2, carried forward to the subsequent environmental time increment is then adjusted for interreceptor

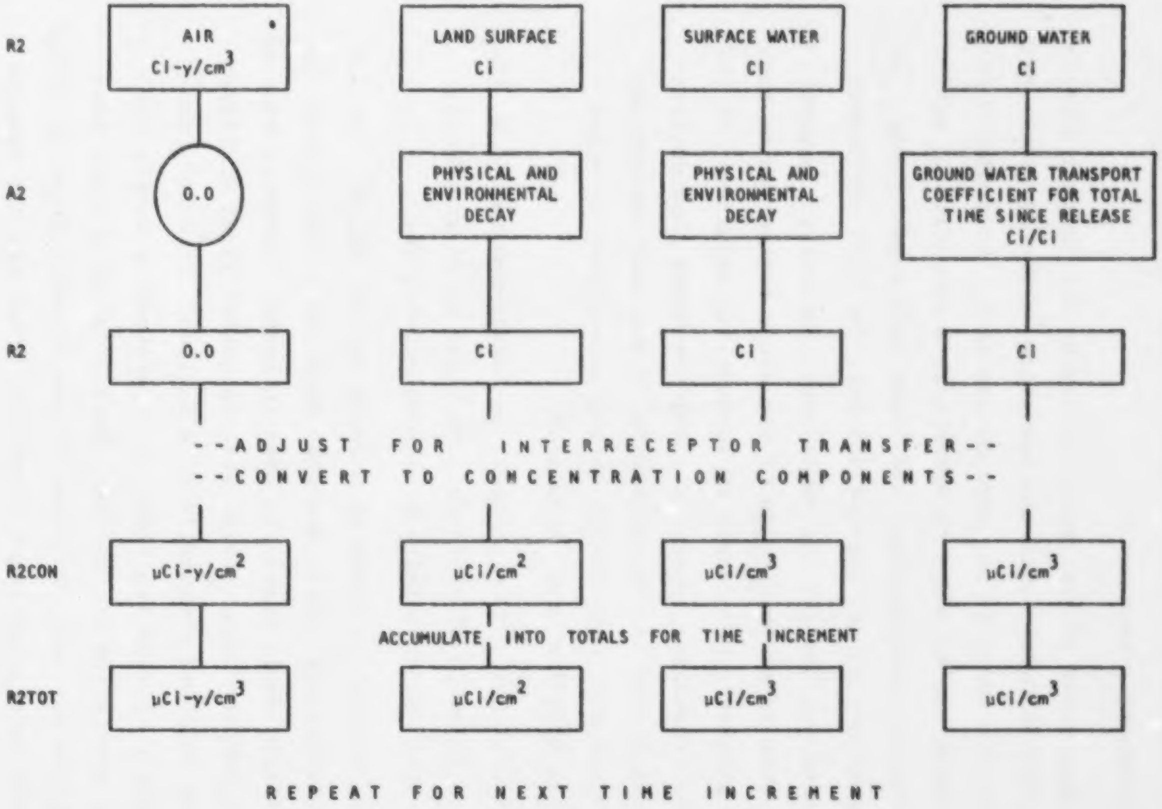

R2
A2
R2
R2CON
R2TOT
AIR
Ci-y/cm³
LAND SURFACE
Ci
SURFACE WATER
Ci
GROUND WATER
Ci
0.0
PHYSICAL AND ENVIRONMENTAL DECAY
PHYSICAL AND ENVIRONMENTAL DECAY
GROUND WATER TRANSPORT COEFFICIENT FOR TOTAL TIME SINCE RELEASE Ci/Ci
0.0
Ci
Ci
Ci
--ADJUST FOR INTERRECEPTOR TRANSFER--
--CONVERT TO CONCENTRATION COMPONENTS--
µCi-y/cm²
µCi/cm²
µCi/cm³
µCi/cm³
ACCUMULATE INTO TOTALS FOR TIME INCREMENT
µCi-y/cm³
µCi/cm²
µCi/cm³
µCi/cm³
REPEAT FOR NEXT TIME INCREMENT

Figure 4 - 11. Sequence for residual activities in time increments subsequent to release.

transfers (described earlier and illustrated in Fig. 4 - 9), converted to concentration components R2CON (also described earlier and illustrated in Fig. 4-10), and accumulated in the net matrix of environmental input concentrations, R2TOT. As indicated in Fig. 4-11, this sequence is repeated from time increment to time increment, over all time subsequent to each release increment considered.

Transfer between zones of the region following the initial dispersion is not provided in AMRAW, with the exception of ground water which can have withdrawal for usage in any appropriate zone. Programming for interzonal adjustment can be added to AMRAW with a sacrifice of additional computer storage, running time, and input data requirements. At this time, the unavailability of appropriate data for this additional model refinement does not justify the additional complexity. However, transfer from any zone to areas outside of the study region can be simulated in AMRAW as presently programmed by appropriate adjustment of the environmental decay constants. Also, it should be noted that environmental effects which accrue to the population in one zone include any components which would otherwise accrue to the populations in other zones if inter-zonal transfer were calculated.

(e) Decay Factors. The physical and environmental decay factors used in the calculation of residual activities in environmental time increments subsequent to a release are described here.

Radiodecay is handled in AMRAW by a decay factor, DECFAC. If all of the selected nuclides had simple one-step decay to a stable form, an exponential calculation could easily be used in AMRAW. However, many of the actinides have complex decay chains with daughters first displaying a buildup with time followed eventually by a decline. In AMRAW, the effective decay factor between two times is determined as simply the ratio of inventory quantities for the two times from AMRAW input data. This may be done since the decay behavior of any released fraction is the same as that for the total repository inventory. That is, the complex decay-buildup equations are done externally by the ORIGEN code, or equivalent, which is more accurate than any simple model which could be used within AMRAW. More specifically, the radiodecay factor for carrying forward the residual activity from one time increment to the next time increment is the ratio of the average inventory in the two adjacent increments. For example, consider two ten-year increments ending at 80 and 90 years respectively, and evaluate the radiodecay factor for Sr-90. The average repository inventory during the first time increment is $(X_{70} + X_{80})/2$, where the X values represent input data: grams of Sr-90 at 70 and 80 years (after start of repository inventory), respectively. Similarly the average inventory during the next time increment, using data from cases in Vol. II, is $(X_{80} + X_{90})/2$. Then the decay factor becomes

$$\mathrm{DECFAC} = \frac{X_{80} + X_{90}}{X_{70} + X_{80}} = \frac{1.91 \times 10^{7} + 1.48 \times 10^{7}}{2.43 \times 10^{7} + 1.91 \times 10^{7}} \qquad (4\text{-}26)$$

$$= 0.781.$$

Using the basic exponential decay relation [My67], activity ~ $\exp(-\lambda\Delta t)$, this factor for a ten-year interval, corresponds to a decay constant of $\lambda = \ln 0.781/(-10) = 0.0247\ y^{-1}$ and hence a half life of $\ln 2/0.0247 = 28.0$ y. This is a reasonable approximation of the literature value of 27.7. It should be noted that the decay factor is dimensionless and evaluation by use of nuclide mass is the same as use of activity. When buildup of a radionuclide occurs over a time interval this is automatically accommodated by this method; a DECFAC value >1.0 indicates buildup. Also, it should be noted that this method properly evaluates an effective decay factor for nuclides in equilibrium with longer lived parents.

Ground water transport calculations are made from the time of release to the beginning and to the end of the subsequent time increment of interest and then averaged. The decay factor in these instances is evaluated with inventory values for the corresponding times.

For ground water calculations where the time increment of interest is large, the increment is subdivided and the intermediate values obtained are included in the average for the whole time increment. The inventory used for each intermediate value of DECFAC is determined by linear interpolation between inventory values for the beginning and end of the whole time increment.

The above discussion applies to the terminal storage phase which considers releases only after a fixed initial inventory has been accumulated. When AMRAW is run for the repository operations phase, potential releases are calculated only for the repository accumulation period.

Evaluation of DECFAC for environmental times which follow the end of the accumulation period proceeds as discussed above. However, during repository operations, the accumulation process masks decay processes and a modified evaluation of DECFAC becomes necessary. For this condition, the decay factor is based upon the factor for the first time increment after closing the repository, with adjustment for the size of the time increment of interest relative to the reference increment. This may be illustrated with an example. Consider: 1) a release during a time increment from 20 to 25 y after start of the repository, 2) repository closing at 30 y, and 3) time increment immediately after closing is from 30 to 40 y. Then,

$$\begin{aligned} \text{DECFAC} &= 1 - \frac{(25 - 30)}{(40 - 30)} \left(1 - X_{40}/X_{30}\right) \\ &= 0.5 + 0.5 \left(X_{40}/X_{30}\right) \\ &= 0.5 \left(1 + X_{40}/X_{30}\right) \end{aligned}$$

For Sr-90, this becomes

$$\text{DECFAC} = 0.5 \ (1 + 4.91 \times 10^7/6.28 \times 10^7) = 0.891$$

which for the five year time interval is within 1% of the 0.882 value which would correspond to the literature value of 27.7 y half-life. For a long lived nuclide, $X_{40} = X_{30}$, and DECFAC becomes 1.0 as it should.

The environmental decay factor is simply $\exp(-\lambda_e \Delta t)$, where λ_e is the environmental decay constant and Δt is the time interval over which the factor is to be applied. λ_e is input to AMRAW as ECD with values for each combination of radionuclide, zone, and receptor.

(f) Ground Water Transport Model. In Section 4.C.2, a multibarrier concept is discussed as it applies to a geologic isolation repository. By selecting a stable geologic structure free from water penetration and by using a high-integrity container, the initiation of release of radioactivity can be prevented or impeded. For a hypothetical breaching of the container, the rate of release can be reduced by selecting a low-leachable solid waste matrix (such as borosilicate

glass) into which the nuclides are incorporated. In addition to these three barriers, there is a fourth barrier provided by the geologic medium surrounding the repository which can impede the migration rate of the nuclides through the geosphere to the biosphere. Here, an analysis of the transport processes of the last barrier is the domain of ground water transport studies.

In considering movement of solutes (dissolved nuclides) through the geologic medium it is well understood that generally solutes move due to the convective movement of the transporting solution, in this case water. In addition, other complex physico-chemical interactions such as solid-phase sorption, hydrodynamic dispersion and diffusion also act to control the movement of solutes relative to the solvent [Br74]. The effect of these interactions is thus to cause the nuclides to move at generally lower velocities compared to the velocity of the water and, also taking into account radioactive decay, result in the consequent reduction of releases to the biosphere [Bu76].

(1) Flow in Saturated-Unsaturated Porous Media. Consider the case of instantaneous release of radioactive waste from a storage tank. Essentially this type of release first brings the waste into contact with the soil moisture moving as unsaturated flow. The predominant direction of unsaturated flow is vertically downward until the flow reaches the saturated zone where the moisture content on a volumetric basis, θ, has reached effective porosity ϵ (i.e., $\theta = \epsilon$) and flow is mainly lateral. In some sites [EPA75] the unsaturated zone (i.e., $\theta < \epsilon$) may be sufficiently thin so that interactions during transport may be considered small. In other sites, like the Los Alamos low-level burial site [EPA75], the unsaturated zone may be so thick that it may be difficult to characterize an interaction between the burial ground and the main aquifer underneath.

Consider further a different type of release whereby interconnection of aquifers by offset faulting (Fig. 4-12) introduces ground water into the disposal horizon and allows it to come into contact with the inventory of waste (container failure is assumed here for purposes of analysis). The contaminated ground water leachant may then move through the disposal formation and into the upper aquifer as shown in Fig. 4-12.

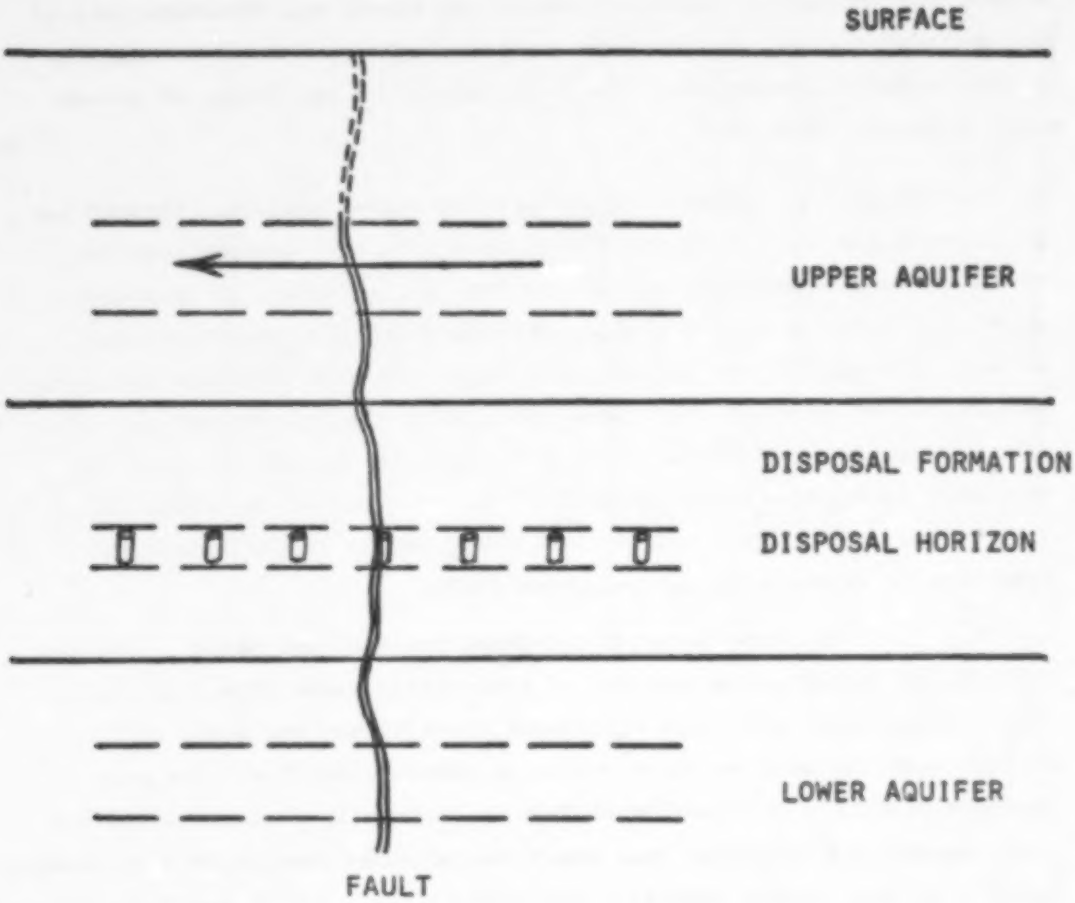


Figure 4 - 12. Movement of leachant from disposal horizon to upper aquifer.

For this release scenario, the upward movement through the disposal formation can be considered equivalent to the downward movement unsaturated flow described previously in the release from the waste tank storage.

(2) Generalized Formulation for Ground Water Transport. The equations governing ground water transport through saturated-unsaturated media may be formulated in the most general form by first assuming that, where flow of both air and water is involved, the air phase is continuous and is at atmospheric pressure; therefore, there are

no air pockets trapped in the main ground water flow system [Re75].

The generalized formulation for flow in saturated-unsaturated porous media as developed by Duguid and Reeves [Re75, Du76, ANS] consists of the following: a) equation of continuity of the fluid, b) equation of continuity of the solid, c) equation of motion of the fluid, d) consolidation equation for the medium, and e) equation of state for the compressibility of water. Combination of all of these equations will yield one governing equation for flow through porous media [Re75].

The equation of continuity of the fluid [Co66] is given by

$$\frac{\partial}{\partial t}\left(\phi\varepsilon\rho_f\right) + \nabla\cdot\left(v_s\,\phi\varepsilon\rho_f\right) = -\nabla\cdot\left(\rho_f\,v_{fs}\right) \qquad (4\text{-}27)$$

where ϕ is the saturation i.e., volumetric fraction of porosity which is solid, and v_{fs} is the velocity of the fluid relative to the solid [Re75]. Bird [Bi60] defines v_{fs} as the superficial velocity, i.e., the volume rate of fluid through a unit cross sectional area of solid plus fluid. The velocity of the solid, v_s is carried here to keep the equations general but this parameter is not retained for the simplified formulation presented later. The term velocity is used here interchangeably with the Darcian flux of fluid relative to the solid. The equation of continuity for incompressible solids is

$$\frac{\partial}{\partial t}(1-\varepsilon) + \nabla\cdot\left(v_s(1-\varepsilon)\right) = 0. \qquad (4\text{-}28)$$

Here, the term $(1-\varepsilon)$ represents the volume concentration of the solids.

For anisotropic media the equation of motion of the fluid is represented by Darcy's law [Sc74] given by

$$v_{fs} = -\bar{\bar{K}}\cdot\nabla H \qquad (4\text{-}29)$$

where $\bar{\bar{K}}$ is the hydraulic conductivity tensor and H is the total hydraulic head. Generally, the tensor $\bar{\bar{K}}$ accounts for directional properties (anisotropy) that arise in formations such as layered sediments. It is defined as

$$\overline{\overline{K}} = \frac{\overline{\overline{k}}\,\rho_f g}{\mu_f} \qquad (4-30)$$

where $\overline{\overline{k}}$ is the intrinsic permeability tensor, g is the gravitational factor, and μ_f is the fluid viscosity. If a continuous saturated-unsaturated flow domain exists, then the total hydraulic head H at elevation z, relative to an arbitrary datum z_o can be expressed in the manner defined by DeWiest [Dw65, Re75], i.e.,

$$H = \frac{1}{g}\left(g\int_{z_o}^{z_1} dz + \int_{p_o}^{p_1} \frac{dp}{\rho_f}\right) = \left(z_1 - z_o\right) + \frac{p_1 - p_o}{\rho_f g} . \qquad (4-31)$$

The term p_1 is the pressure at elevation z_1, and p_o is the pressure at the arbitrary datum z_o. Thus H may be written, using consistent units, as

$$H = z + h \qquad (4-32)$$

where

$$z = z_1 - z_o \quad \text{and} \quad h = \frac{p_1 - p_o}{\rho_f g} = \frac{\sigma}{\rho_f g} \qquad (4-33)$$

where σ represents the incremental pressure in the fluid. Substitution of Eq. 4 - 32 into Eq. 4 - 29 yields the resulting equation of motion

$$v_{fs} = -\overline{\overline{K}} \cdot (\nabla h + \nabla z). \qquad (4-34)$$

Although Eq. 4 - 28 considers the grains of the solid medium to be incompressible, the granular skeleton of the medium as a whole is considered to be compressible, in which case the geometric quantities describing porous media may be functions of certain dynamic quantities, notably of the existing stress [Sc74]. Thus in a study on the consolidation of porous media, Biot [Bm40] developed the three-dimensional consolidation equation [Re75] given by

$$(\lambda_s + 2\eta_s)\ \nabla^2\tau = \nabla^2\sigma \qquad (4-35)$$

where λ_s and η_s are the Lame' constants, τ is the dilatation of the medium, and the term $\nabla^2\sigma$ represents the total stress. The dilatation is defined as

$$\tau = \xi_{kk} \tag{4-36}$$

where ξ_{ij} is the macroscopic strain tensor, i.e. of the bulk of the medium. (In a study of flow through porous media, the flow of fluids and not the consolidation of the medium is of primary interest in general.)

The equation of state for the fluid compressibility β' [Dn68] is, for an isothermal case

$$\rho_f = \rho_f^{*} e^{\beta(p_1 - p_o)} = \rho_f^{*} e^{\beta' h}$$

$$\beta' = \beta \rho_f g. \tag{4-37}$$

The ρ_f^{*} here is the fluid density at pressure p_o, and β' is the modified coefficient of compressibility of water. The term h is defined in Eq. 4-33.

At this point a number of functional relationships should be noted before continuing with the formulation of the generalized flow equation. As indicated by Eq. 4 - 37, the fluid density ρ_f is a function of pressure head. The hydraulic conductivity (often called permeability and seepage coefficient) and the porosity ε are both functions of position and pressure head [Re75], i.e.,

$$\overline{\overline{K}} = \overline{\overline{K}}(x, h) \tag{4-38}$$

$$\varepsilon = \varepsilon(x, h) \tag{4-39}$$

where x is a position vector. In saturated regions the dependence of $\overline{\overline{K}}$ on space is due only to nonhomogeneity of the medium, and in unsaturated regions $\overline{\overline{K}}$ varies both with position and time even in homogeneous media due to its dependence on pressure head [Re75].

The porosity ε and saturation ϕ (Eq. 4-27) may be used to define the volumetric moisture content θ, such that

$$\theta(x, h) = \phi(x, h)\ \varepsilon(x, h). \qquad (4\text{-}40)$$

Eq. 4 - 40 simply shows that as the medium approaches saturation ($\phi \rightarrow 1$), the moisture content approaches the numerical value of the porosity of the medium.

Equations 4-27 and 4-28 can be written first in expanded forms and then combined to yield the resultant expression

$$\varepsilon\rho_f \frac{\partial \phi}{\partial t} + \phi\varepsilon \frac{\partial \rho_f}{\partial t} + \phi\rho_f \nabla \cdot v_s$$

$$+ \nabla \cdot \left(\rho_f v_{fs}\right) + \varepsilon v_s \nabla \cdot \left(\phi\rho_f\right) = 0. \qquad (4\text{-}41)$$

The last term in Eq. 4 - 41 is essentially a higher-order effect and may be neglected [Re75], thus

$$\varepsilon\rho_f \frac{\partial \phi}{\partial t} + \phi\varepsilon \frac{\partial \rho_f}{\partial t} + \phi\rho_f \nabla \cdot v_s$$

$$+ \nabla \cdot \left(\rho_f v_{fs}\right) \doteq 0. \qquad (4\text{-}42)$$

The equation of motion (Eq. 4 - 34) can be multiplied by ρ_f and the divergence of the result obtained to give

$$\nabla \cdot \left(\rho_f v_{fs}\right) = - \nabla \cdot \left|\rho_f \bar{K} \cdot (\nabla h + \nabla z)\right|. \qquad (4\text{-}43)$$

When Eq. 4 - 43 is substituted into Eq. 4 - 42 the following equation is obtained

$$\varepsilon\rho_f \frac{\partial \phi}{\partial t} + \phi\varepsilon \frac{\partial \rho_f}{\partial t} + \phi\rho_f \nabla \cdot v_s$$

$$= \nabla \cdot \left|\rho_f \bar{K} \cdot (\nabla h + \nabla z)\right| . \qquad (4\text{-}44)$$

Eq. 4 - 44 can be simplified by searching for a relation for the gradient $\nabla \cdot v_s$. The porosity may not vary considerably with the pressure head h, in which case chain-rule differentiation on Eq. 4 - 40 yields

$$\frac{d\theta}{dh} = \varepsilon \frac{\partial \phi}{\partial h} , \qquad (4\text{-}45)$$

from which it also follows that

$$\frac{d\theta}{dh} \frac{\partial h}{\partial t} = \varepsilon \frac{\partial \phi}{\partial h} \frac{\partial h}{\partial t} = \varepsilon \frac{\partial \phi}{\partial t} . \qquad (4\text{-}46)$$

Assuming a constant modified coefficient of compressibility of water, β', the fluid density given by the equation of state (Eq. 4 - 37) is differentiated with respect to time to give

$$\frac{\partial \rho_f}{\partial t} = \beta' \left(\rho_f^* \ e^{\beta' h} \right) \frac{\partial h}{\partial t}$$

$$= \beta' \rho_f \frac{\partial h}{\partial t} . \qquad (4\text{-}47)$$

The equation for consolidation of the medium (Eq. 4 - 35) is seen as a second-order derivative, and when integrated twice, yields

$$\left(\lambda_s + 2\eta_s \right) \tau = \sigma + f \qquad (4\text{-}48)$$

where $f = f(x, t)$. The function f here must satisfy the Laplace equation $\nabla^2 f = 0$ for all time [Re75], i.e. this condition enables Eq. 4-48 to transform back to Eq. 4-35 when Eq. 4- 48 is double-differentiated. The Lame' parameters λ_s and η_s are considered constant. For the case where all the displacement u is in the vertical direction, e.g. $u = u_{zz}$, it was shown [Dw69, Re75] that $f = 0$. Thus from Eq. 4 - 48

$$\frac{\partial \tau}{\partial t} = \alpha \frac{\partial \sigma}{\partial t}$$

$$\alpha = 1/\left(\lambda_s + 2\eta_s \right) . \qquad (4\text{-}49)$$

The lumped parameter α is the coefficient of consolidation of the medium.

Introduce the transformations

$$v_s = \frac{\partial u}{\partial t} \qquad \gamma = \nabla \cdot u. \tag{4-50}$$

Now

$$\nabla \cdot v_s = \nabla \cdot \left(\frac{\partial u}{\partial t}\right) \tag{4-51}$$

but since u is considered a continuous function, the operational order on Eq. 4 - 51 is immaterial, thus

$$\nabla \cdot v_s = \frac{\partial}{\partial t}\,(\nabla \cdot u) = \frac{\partial \gamma}{\partial t}\,. \tag{4-52}$$

The expression for h in Eq. 4 - 33 can be written

$$\sigma = \rho_f g h$$

which is substituted into Eq. 4 - 49 to give

$$\frac{\partial \gamma}{\partial t} = \alpha\,\rho_f g\,\frac{\partial h}{\partial t} \tag{4-53}$$

or

$$\frac{\partial \gamma}{\partial t} = \alpha'\,\frac{\partial h}{\partial t} \tag{4-54}$$

$$\alpha' = \alpha\,\rho_f g. \tag{4-55}$$

Here, α' is the modified coefficient of compressibility of the medium. Eq. 4 - 54 is next combined with Eq. 4 - 52 to obtain $\nabla \cdot v_s$, i.e.

$$\nabla \cdot v_s = \alpha'\,\frac{\partial h}{\partial t}. \tag{4-56}$$

Finally, Eqs. 4 - 40, 4 - 46, 4 - 47, and 4 - 56 are substituted into Eq. 4 - 44 to yield the governing equation for saturated-unsaturated flow in porous media

$$\left| \frac{\theta}{\varepsilon} \alpha' + \theta\beta' + \frac{d\theta}{dh} \right| \frac{\partial h}{\partial t} = \nabla \cdot \left| \overline{K} \cdot (\nabla h + \nabla z) \right| . \qquad (4\text{-}57)$$

The terms α' and β' are defined in Eq. 4 - 55 and Eq. 4 - 37, respectively; z is the elevation head defined in Eq. 4 - 33.

Inspection of Eq. 4 - 57 shows that it is nonlinear on acccount of the dependence of both the moisture content θ and the conductivity tensor $\overline{K}$ on the pressure head for unsaturated flow. Furthermore, the disadvantage of such a nonlinear formulation in three dimensions is that in a large-basin oriented study, the added numerical computational complexity practically restricts the size of the region that may be modeled.

The following is a discussion of a simplified version of the Duguid-Reeves solution [Re75] of the generalized flow formulation, giving a one-dimensional flow with two-dimensional dispersion relation which is adapted in this analysis.

(3) Simplified Formulation for Ground Water Transport. Strictly, the governing formulation for saturated-unsaturated flow in porous media (Eq. 4-57) is valid for both saturated and unsaturated flow because the unsaturated region is considered in the movement of the species from the point of release through the unsaturated zone to the water table (saturated zone) where flow is mainly lateral. The Duguid-Reeves transient model [Re75, Du76, ANS] is first discussed here before presenting a simplified version of that model, which is used in AMRAW. This model and a number of one-dimensional models [Ch69, Kn64, Ls74, Rt72] were studied to ascertain which predictive method to use in determining the effects of solid-liquid phase interactions on the movement of dissolved nuclides in porous media. The Duguid-Reeves model is now in "Standards for Evaluating Radionuclide Transport in Ground Water at Nuclear Power Sites," American National Standards ANS-2.17 (in review) [ANS].

For saturated-unsaturated flow, both a vertical dimension and a horizontal dimension are considered, generating a vertical plane. The equation of motion for the fluid given by Eq. 4-34 along with the governing formulation for flow (Eq. 4-57) are written together to form a coupled set of equations

$$v_{fs} = -\,\overline{\overline{K}} \cdot (\nabla h + \nabla z) \tag{4-34}$$

$$\left|\frac{\theta}{\varepsilon}\alpha' + \theta\beta' + \frac{d\theta}{dh}\right| \frac{\partial h}{\partial t} = \nabla \cdot \left|\overline{\overline{K}} \cdot (\nabla h + \nabla z)\right|. \tag{4-57}$$

From these equations, a single equation can be written in which the Darcy flux (v_{fs}) appears as a variable, i.e.

$$\left|\frac{\theta}{\varepsilon}\alpha' + \theta\beta' + \frac{d\theta}{dh}\right| \frac{\partial h}{\partial t} = -\,\nabla \cdot v_{fs}. \tag{4-58}$$

For a defined position vector x, the conductivity tensor $\overline{\overline{K}}$ is a function of pressure head, namely $\overline{\overline{K}} = \overline{\overline{K}}(h)$; this is verified by the form of Eq. 4 - 38. When flow interactions in the unsaturated zone are considered negligible (i.e. the unsaturated zone is sufficiently thin), then only saturated flow in the lateral direction is considered. Thus, from Eq. 4 - 40, $\theta \to \varepsilon$ as $Ø \to 1$, and Eq. 4 - 57 becomes

$$(\alpha' + \theta\beta') \frac{\partial h}{\partial t} = \nabla \cdot \left|\overline{\overline{K}} \cdot (\nabla h + \nabla z)\right|. \tag{4-59}$$

As was pointed out in an earlier discussion in this section, the conductivity tensor accounts for directional properties (anisotropy). If the coordinate system is selected such that it is made parallel to the principal components of conductivity, then only the principal components of the tensor are required [Re75]. Assuming further that the solid medium is homogeneous and isotropic, in which case the conductivity will not vary with direction, the tensor $\overline{\overline{K}}$ reduces to a scalar [Bi60, Kr67], i.e. $\overline{\overline{K}} \to K$. Equation 4- 34 thus becomes

$$v_{fs} = -\,K\,(\nabla h + \nabla z) \tag{4-60}$$

and using this result, Eq. 4 - 59 takes the corresponding form

$$(\alpha' + \theta\beta') \frac{\partial h}{\partial t} = K\,\nabla \cdot (\nabla h + \nabla z) \tag{4-61}$$

where α' and β' are defined in Eq. 4 - 55 and Eq. 4 - 37, respectively

$$\alpha' = \alpha\rho_f g \tag{4-55}$$

$$\beta' = \beta \rho_f g \tag{4-37}$$

In dealing with saturated flow, a generalized storage coefficient F is defined such that

$$F = \alpha' + \theta \beta'$$

or, using Eqs. 4 - 55 and 4 - 37,

$$F = \rho_f g \ (\alpha + \theta \beta) \tag{4-62}$$

Substituting Eq. 4 - 62 into Eq. 4 - 61, the result is

$$F \frac{\partial h}{\partial t} = K \nabla \cdot (\nabla h + \nabla z). \tag{4-63}$$

The definition for the total hydraulic head given in Eq. 4 - 32

$$H = h + z \tag{4-32}$$

is used in Eq. 4 - 63 to obtain

$$F \frac{\partial h}{\partial t} = K \nabla \cdot \nabla (h + z)$$

$$= K \nabla^2 H$$

or, rearranging

$$\nabla^2 H = \frac{F}{K} \frac{\partial h}{\partial t} \tag{4-64}$$

For saturated (lateral) flow, the elevation head z is a defined quantity (constant), and Eq. 4 - 64 can be written in general [Kr67]

$$\nabla^2 H = \frac{F}{K} \frac{\partial H}{\partial t} . \tag{4-65}$$

The Duguid-Reeves model [Re75] considers Eq. 4 - 64 to be valid for both confined and unconfined aquifers.

Consider a confined aquifer of thickness w. Next define a storage constant F_o and a transmissivity T_o such that

$$F_o = Fw \qquad T_o = Kw. \tag{4-66}$$

Substituting these definitions (Eq. 4 - 66) into Eq. 4 - 65 yields Eq. 4 - 67

$$\nabla^2 H = \frac{F_o}{T_o}\frac{\partial H}{\partial t}. \tag{4-67}$$

Duguid and Reeves note that in using this predictor relation, the boundary conditions of leakage should be applied when appropriate.

For the case of flow through an unconfined aquifer, the modified compressibilities of both the solid medium (α') and the water (β') are not significant compared to the vertical movement of the free surface (water table) [Re75]. Thus Eq. 4 - 67 simply reduces to

$$\nabla^2 H = 0 \tag{4-68}$$

which is the Laplace equation [Kr67]. Equation 4 - 68 is valid for steady-state flow in confined and unconfined aquifers [Re75].

A further approximation of the equation of motion (Eq. 4 - 60) for the fluid velocity v_{fs} (also termed Darcy flux in this analysis) can be obtained next. If the predominant bulk flow is in the x-direction, Eq. 4 - 60 along with Eq. 4 - 32 can be written

$$v_{fs}\big|_x = - K \nabla H = - K \frac{dH}{dx}. \tag{4-69}$$

The gradient dH/dx relates to the basic concept of a continuum. Thus, from elementary calculus [Kr67] Eq. 4 - 69 can be approximated

$$v_{fs}\big|_x \doteq - K \frac{\Delta H}{\Delta x}. \tag{4-70}$$

The term $\Delta H/\Delta x$ is the approximate hydraulic gradient in the direction of the flow (x-direction); it is constant over the increment Δx for a homogeneous, isotropic solid medium.

The pore velocity (also called seepage velocity) is obtained by dividing the fluid velocity in the x-direction, $v_{fs}\big|_x$, by the effective porosity [Bi60, Re75].

(4) Simplified Formulation for Radionuclide Mass Transport. A formulation for the general movement of the carrier fluid (water) has so far been discussed. In order to completely describe the movement of dissolved constituents (radionuclides) in ground water through porous media, a formulation for the mass transport of the radionuclides must also be obtained.

It was pointed out at the beginning of this section that, with respect to the migration of radionuclides, these nuclides may have complex physico-chemical interactions with the geologic medium [Bu76]. These interactions, which fall under the general category of sorption, can cause the nuclides to move at velocities lower than the carrier water itself. In general, some nuclides (e.g. Th-229, Th-230) are very strongly sorbed on many geologic media; others (Sr-90, Np-237) are moderately sorbed, while nuclides like I-129 and Tc-99 are sorbed very poorly, if at all [Bu76, Rt73a].

A measure of the retention of the species on the porous medium is called the distribution coefficient K_d [Bu76, Gf74, Gv66, Lv72]. In general, K_d is a function of the pH of the ground water, the concentration of dissolved salts (e.g. sodium chloride), solution temperature, and in some cases, concentration of the dissolved nuclides themselves [Bu76]. Equilibrium condition are assumed for all relative physical processes.

Symbolically, K_d can be represented by

$$K_d = \frac{f_m}{f_s} \tag{4-71}$$

where f_m is the fraction of the amount of species that is sorbed on the solid medium per unit mass of the medium, and f_s is the fraction of the amount of species remaining in the solution per unit volume of solution. The usual units of K_d are in cm^3/g. Simply, a higher K_d means strong sorption, and conversely; Th-229, for example, has a K_d over 10,000, while I-129 has a K_d near zero [Rt73a].

A retardation factor R_d is defined such that

$$R_d = 1 + \frac{\rho K_d}{\varepsilon} \qquad (4-72)$$

where ρ is the bulk density of the porous medium and ε is the solid porosity defined in Eq. 4 - 39. Here, ρ must have units of g/cm^3 to obtain a dimensionless R_d. The pore velocity is normally divided by R_d to obtain a measure of the approximate rate of travel of the radionuclide (see Eq. 4 - 80 in subsequent discussion).

The most general form of the single species radionuclide mass transport equation for saturated-unsaturated media as developed by Duguid and Reeves [Du76, ANS] is given by

$$R_d\ \theta \frac{\partial c}{\partial t} - \nabla \cdot (\theta \overline{\overline{D}} \cdot \nabla c) + \nabla \cdot (v_{fs} c) + (R_d \frac{\partial \theta}{\partial t} + \lambda \theta R_d c) = 0 \qquad (4-73)$$

where c is the concentration of the dissolved species, $\overline{\overline{D}}$ is the dispersion tensor, and λ is the radioactive decay constant.

In general, for simulation of radionuclide transport, Eq. 4 - 73 may be used together with either Eqs. 4 - 34 and 4 - 58 or Eqs. 4 - 34 and 4 - 59. Duguid and Reeves [Re75] observed that in a numerical solution of Eqs. 4 - 34 and 4 - 58 in conjunction with Eq. 4 - 73, the components of the flux will be discontinuous where the advective-transport term $\nabla \cdot (v_{fs} c)$ is comparable to or greater than the dispersion term (second term in Eq. 4 - 73). In the case of fine-grained sediments where the coefficient of dispersion is small, Duguid and Reeves recommend using Eqs. 4 - 34 and 4 - 59.

The Duguid-Reeves transient model [Re75] employs a finite-element Galerkin method to numerically solve Equation 4-73 along with Eqs. 4 - 34 and 4 - 59, for instance. The method was shown to be superior to other numerical methods previously used, in that stability was significantly increased. As a result of improved stability, Duguid and co-worker were able to increase step increments in size and time accordingly, thereby reducing the computer time and storage core required. However, the average computing time for this procedure is approximately 4 1/2 minutes. Because of the computational nature of the

AMRAW code itself, this numerical method was not adapted for use in the ground water transport calculations in AMRAW; instead, a simplified analytical solution is the basis of the ground water transport algorithm employed in this analysis.

In the mass transport equation (Eq. 4 - 73), it should be pointed out that the dispersivity $\overline{D}$ is generally a fourth-rank tensor which contains 3^4 or 81 components. If isotropy is assumed, however, it can be related to two constants: namely, longitudinal and transverse dispersivities [ANS]. The longitudinal and transverse components of dispersivity can be obtained from tracer studies conducted in the aquifer under investigation.

The component, D_{ij}, of the dispersion tensor for isotropic media has the general form [Re75]

$$D_{ij} = \frac{a_T}{\theta} v \ \delta_{ij} + \frac{(a_L - a_T)}{\theta} v_i v_j / |v| \qquad (4\text{-}74)$$

where δ_{ij} is the Kronecker delta [Bi60, Kr67], a_T and a_L are the transverse and longitudinal dispersivities, respectively, $|v|$ is the magnitude of the Darcy flux, and v_i and v_j are the components of the Darcy flux. Note that the subscript fs in the previous Darcy flux term (v_{fs}) has been dropped for simplicity.

The following major assumptions provide a simplification to the radionuclide mass transport equation (Eq. 4 - 73), and form an important basis for the simplified Duguid-Reeves two-dimensional model itself: 1) the porous medium is infinite, homogeneous, and isotropic with simple boundary conditions; 2) porous region is fully saturated; 3) sorption of the dissolved radionuclide species is governed by a linear relationship; 4) mechanical dispersion is dominant over molecular diffusion; 5) chemical reactions are rapid such that instantaneous equilibrium exists between the dissolved and sorbed constituents; 6) fluid flow is uniform and steady; 7) flow is parallel to the x-axis; 8) concentration of the radionuclide species in the soil region is zero at time equals zero; and 9) a single species without a decay source is considered.

The use of the second assumption above yields $\theta \to \varepsilon$ as $\emptyset \to 1$, and Eq. 4 - 73 becomes

$$R_d \frac{\partial c}{\partial t} - \nabla \cdot (\overline{D} \cdot \nabla c) + \nabla \cdot (\frac{v}{\varepsilon} c) + \lambda R_d c = 0. \qquad (4\text{-}75)$$

Also, from assumption 6, the Darcy flux v can be considered constant, thus Eq. 4 - 75 reduces to

$$R_d \frac{\partial c}{\partial t} - \nabla \cdot (\overline{D} \cdot \nabla c) + \frac{v}{\varepsilon} \cdot \nabla c + \lambda R_d c = 0. \qquad (4\text{-}76)$$

If the dispersion tensor is assumed to apply to a homogeneous but anisotropic solid medium, then using assumption 7, Eq. 4-76 may be written in a form giving two-dimensional dispersion with one-dimensional flow as

$$R_d \frac{\partial c}{\partial t} - \left(D_{xx} \frac{\partial^2 c}{\partial x^2} + D_{yy} \frac{\partial^2 c}{\partial y^2}\right) + \frac{v_x}{\varepsilon} \frac{\partial c}{\partial x} + \lambda R_d c = 0 \qquad (4\text{-}77)$$

where the components of the coefficient of dispersion are given in Eq. - 74 as

$$D_{xx} = a_L \frac{v_x}{\varepsilon} \qquad D_{yy} = a_T \frac{v_x}{\varepsilon}. \qquad (4\text{-}78)$$

The term v_x is the fluid velocity (as distinguished from pore velocity which was defined earlier as fluid velocity divided by the effective porosity) in the predominant x-direction of flow; a_L and a_T are the longitudinal and transverse dispersivities, respectively, and should be determined from in-situ studies in the aquifer. Dividing Eq. 4 - 77 by R_d yields

$$\frac{\partial c}{\partial t} - E_x \frac{\partial^2 c}{\partial x^2} - E_y \frac{\partial^2 c}{\partial y^2} + U \frac{\partial c}{\partial x} + \lambda c = 0 \qquad (4\text{-}79)$$

$$E_i = \frac{D_{ii}}{R_d} \qquad U = \frac{1}{R_d} \frac{v_x}{\varepsilon}. \qquad (4\text{-}80)$$

Here, U is called the pulse velocity, and is the approximate rate of travel of the dissolved radionuclide and can be used to estimate the approximate travel time of the species [ANS].

Eq. 4 - 79 can also be written

$$\frac{Dc}{Dt} - E_x \frac{\partial^2 c}{\partial x^2} - E_y \frac{\partial^2 c}{\partial y^2} + \lambda c = 0 \qquad (4\text{-}81)$$

where

$$\frac{Dc}{Dt} = \frac{\partial c}{\partial t} + U\,\frac{\partial c}{\partial x}\ .$$

The term Dc/Dt is a special kind of total derivative and is called [Bi60] the "substantial derivative" or, more logically, the "derivative following the motion" of the radionuclide in the x-direction.

Although for saturated-unsaturated flow with two-dimensional dispersion the vertical and horizontal dimensions must be considered, the resulting rectangular plane source approaches that for a line source as the distance from the source becomes large compared to the source width [ANS]. Appendix A provides development of the equivalent line source equation from a plane source equation. Hence, for the instantaneous release from a vertical line source through the point (x_1, y_1), the analytical solution to the simplified transport equation (Eq. 4-79) is

$$C = \frac{M'}{4\pi\ (E_x E_y)^{\frac{1}{2}} t}\ \exp - \left\{ \frac{\left[(x-x_1) - Ut\right]^2}{4E_x t} + \frac{(y-y_1)^2}{4E_y t} + \lambda t \right\}. \qquad (4\text{-}82)$$

The term M' may be calculated by dividing the amount of a particular radionuclide released by leaching during a release time interval (discussed in Section 3.C) by the thickness of the aquifer in which the waste is released.

If the nuclide is first treated as a "stable nuclide," then the last term λt in Eq. 4 - 82 may be dropped, and Eq. 4 - 82 simply becomes

$$C = \frac{M'}{4\pi\ (E_x E_y)^{\frac{1}{2}} t}\ \exp - \left\{ \frac{\left[(x-x_1) - Ut\right]^2}{4E_x t} + \frac{(y-y_1)^2}{4E_y t} \right\}. \qquad (4\text{-}83)$$

As explained below, radiodecay is later accounted for in a separate step.

Because of the nature of the calculational procedure within AMRAW, the final equation above (Eq. 4 - 83) is the basis of the following Equation 4-84 that is applied within AMRAW to predict radionuclide concentrations in ground water at points of usage or discharge to the surface. Following calculation of concentration at the usage or emergence point, a decay factor (DECFAC) is applied to account for radiodecay. This DECFAC factor and its application is discussed in Paragraph 3.D.1.e of this chapter. Separate calculation for one nuclide at a time with Eq. 4-83 or Eq. 4-84, followed by adjustment for decay (or buildup) by DECFAC, needs some interpretation. If the radionuclide of interest has no radioactive parent, has a short-lived radioactive parent, or if a radioactive parent has the same K_d as the daughter, the simplified method described here correctly accounts for decay and for a decay source with no further adjustment. A short-lived daughter of a long-lived parent may be approximated by setting the K_d value for the daughter equal to K_d for the parent; the daughter inventory in this case is dependent upon the parent and in effect, moves with the parent. If both parent and daughter are long-lived, the method described here overstates daughter concentrations if the daughter moves faster than the parent and understates daughter concentrations if the daughter moves slower than the parent. An intermediate value of K_d assigned to the daughter in such a case can provide an approximate corrected representation. A complete interpretation of the validity of these simplified calculations depends upon inspection of the K_d values determined for a specific site for the nuclides in decay groups to be considered in conjunction with water velocities, travel distances, and other aquifer parameters. For nuclides where the travel time to a usage or discharge point exceeds the time range to be calculated (i.e., K_d exceeds a "border value;" see Section 7.A.2.a. in Volume II), the calculation method becomes moot.

The definitions given in Eqs. 4 - 72, 4 - 78, and 4 - 80 are used to write Eq. 4 - 84, relative to the point ($x_1 = 0$, $y_1 = 0$)

$$C = \frac{k_1}{v_p t} \exp - \left\{ \frac{(x - k_2 v_p t)^2}{k_3 v_p t} + \frac{y^2}{k_4 v_p t} \right\} \qquad (4\text{-}84)$$

where

$$k_1 = \frac{M'}{4\pi (a_L a_T)^{1/2} / R_d} \qquad k_2 = \frac{1}{R_d} \qquad k_3 = 4\,\frac{a_L}{R_d} \qquad (4\text{-}84a)$$

$$k_4 = 4\,\frac{a_T}{R_d} \qquad M' = \frac{M}{z_a} \qquad R_d = 1 + \frac{\rho K_d}{\varepsilon} \qquad (4\text{-}84b)$$

Here, v_p is the pore (or seepage) velocity $\left(= \frac{v_x}{\varepsilon}\right)$, and z_a is the aquifer thickness. Eq. 4 - 84 is in a subprogram CRATIO in AMRAW.

Equation 4-84 obtains the concentration in ground water at time t, distance x from the source, and at a distance y from the plume centerline for specified aquifer and nuclide parameters. At y = 0, the concentration is a maximum and it drops off rapidly with distance from the centerline. It is shown in Appendix A (Eq. A-15) that there is a value of y, where

$$y = y_y = 2.08(a_T x)^{1/2} , \qquad (4\text{-}84c)$$

at which the concentration calculated by Eq. 4-84 is equal to the average concentration across the plume width (in the vicinity of the peak with respect to time). This is the basis of input to AMRAW-A for the corresponding zone-dependent parameter YY. Appendix A also shows that the effective width (width = 2y) of plume where the concentration drops to 0.1% of a value at the peak, from Eq. A-14, is

$$y_w = 10.5(a_T x)^{1/2} . \qquad (4\text{-}84d)$$

The value y_w is input to AMRAW as the zone-dependent parameter YW. The subprogram CRATIO in AMRAW first determines the average concentration across the plume per Ci released, by using $y = y_y$ as explained above. This concentration is (μCi/cm^3)/Ci or (Ci/m^3)/Ci. Next, CRATIO calculates the volume of water with the calculated average concentration which seeps past the location of interest during a time increment (or sub-time intervals). This volume (denoted in CRATIO as GNDDIS or GNDING) is calculated as the product of the effective plume width y_w, aquifer thickness z_a, seepage velocity v_p, porosity ϵ, and the duration of the time increment. The product of concentration per Ci released, (Ci/m^3)/Ci; and the associated water volume, m^3, is dimensionless (Ci/Ci), representing Ci passing the location of interest during a time increment, per Ci released at an earlier time. This product, denoted as CRATIO in subprogram CRATIO, is returned to subprogram TRINP (see previous Section 4.D.1.d and Fig. 4-11) where it is averaged for sub-intervals in the time increment (see a following paragraph for discussion of sub-intervals) and adjusted for radiodecay. Finally, the transfer coefficient A2 (Fig. 4-11) emerges for use in the main program, where multiplication of A2 by a quantity released in Ci obtains the quantity in Ci passing the location of interest during the time increment.

An example calculation is presented here to illustrate application of Eq. 4-84 and the subsequent calculations in predicting radionuclide concentrations at some usage point, e.g., at 10 km from the repository area. Consider an offset fault which results in ground water coming in contact with a portion of the canisters in the repository inventory, and that this event constitutes a leach incident. Consider further that this leach incident takes place during the time interval 900 - 1000 years (after beginning of repository operations), and release of C-14 by leaching is being studied. Then, as was determined in the example calculation for leaching given in Section 4.C.2, the activity leached into the ground water preliminary input receptor during the time interval of interest is 10.1 Ci. However, AMRAW first calculates a transfer coefficient normalized to a 1 Ci release and then applies the coefficient to the calculated release.

Next consider that the contaminated ground water, normalized to a 1 Ci release, enters an unconsolidated aquifer with the following properties taken from the application in Volume II: $v_p = 1.46$ m/y; $\varepsilon = 0.15$; $a_L = 50$ m; $a_T = 6$ m; $\rho = 2.3$ g/cm^3; $z_a = 50$ m; and $K_d = 1.4$ cm^3/g. The C-14 concentration is to be determined at a usage point $x = 10{,}000$ m after a time in the environment, assumed here for illustration, of 160,000 years. From Eq. 4-84c, $y = 2.08(6 \times 10{,}000)^{1/2} = 510$ m. The retardation factor can be immediately estimated using Eq. 4-72: $R_d = 1 + (2.3)\ (1.4)/0.15 = 22.47$. Then from Eq. 4-84: $M' = 1/50 = 0.020$ Ci/m; $k_1 = (0.020)\ (22.47)/(4\pi(50 \times 6)^{1/2}) = 0.00208$ Ci/m^2; $k_2 = 1/22.47 = 0.044$; $k_3 = (4)\ (50)/22.47 = 8.9$ m; $k_4 = (4)\ (6)/22.47 = 1.07$ m. Substituting these values in Eq. 4-84, yields the C-14 concentration prior to accounting for decay.

$$C = \frac{0.00208\ \text{Ci/m}^2}{(1.46\ \text{m/y})(160{,}000\ \text{y})} \exp - \left\{ \frac{[10{,}000-(0.044)(1.46)(160{,}000)]^2\ \text{m}^2}{(8.9\ \text{m})(1.46\ \text{m/y})(160{,}000\ \text{y})} \right.$$

$$\left. + \frac{[510]^2\ \text{m}^2}{(1.07\ \text{m})(1.46\ \text{m/y})(160{,}000\ \text{y})} \right\}$$

$$= (8.90 \times 10^{-9}\ \text{Ci/m}^3)(0.340)$$

$$= 3.03 \times 10^{-9} \ \text{Ci/m}^3$$

$$= 3.03 \times 10^{-9} \ \mu\text{Ci/cm}^3 \ .$$

The example calculation is continued after first discussing travel time and the use of sub-intervals of time in AMRAW.

The travel time of the C-14 at the emergence point can be approximated using the pulse velocity U defined in Eq. 4-80: $U = v_p/R_d = (1.46 \text{ m/y})/22.47 = 0.065 \text{ m/y}$. Then,

$$\text{approx. travel time} = \frac{10{,}000 \text{ m}}{0.065 \text{ m/y}} = 154{,}000 \text{ y}.$$

Thus, it would take approximately 154,000 y for the maximum concentration "peak" of C-14 to occur at a distance of x = 10 km.

It is helpful to describe the procedure in estimating the average radionuclide concentration in ground water in AMRAW. Presently, as specified by input data for applications in Volume II, fifty times are used from the start of repository operations up to a time horizon of a million years, with shorter time increments such as 5, 10, 100 and 1,000 y at the beginning and increasing time increments later, such as 10,000 and 100,000 y. Results of preliminary sensitivity analysis runs on the ground water transport model discussed in Section 7.A of Volume II indicate that generally the width of the radionuclide concentration peaks at half-height is more than 2,000 y. This means that for time increments up to 1,000 y (e.g., 9,000 - 10,000 y), the average nuclide concentration is simply taken as the arithmetic average of the concentrations calculated at the beginning and end of the time increment (e.g., at 9,000 and 10,000 y). When the time increments are 10,000 y or higher, however, this simple averaging procedure would be in error because for these large time increments, narrow peaks associated with low K_d values can be "missed." Hence, in AMRAW, each time increment of $\geq$ 10,000 y is subdivided into 1000 y sub-intervals if $K_d < 1$ and each increment $\geq$ 100,000 y is subdivided into 1000 y sub-intervals if $K_d < 1$ and into 20,000 y sub-intervals if $K_d > 1$ (broader peaks permit longer sub-intervals). The concentration is calculated at the end of each time period, and the average concentration is obtained by dividing the sum of all these calculated concentrations by the total number of time periods in the increment. As discussed in earlier Paragraph 4.D.1.e, a decay factor DECFAC is applied to account for radiodecay in all of the components for average concentration calculations. To illustrate the application of DECFAC, continue the example calculation where it is found that the average concentration of C-14 in a plume 10 km from the repository after 160,000 y following release of 1 Ci during a leaching interval from 900 to 1000 y, and prior to accounting for decay is 3.03×10^{-9} μCi/cm^3. The inventory values for C-14 at times of 1000 y, 100,000 y and 200,000 y are 3.59×10^4, 2.26×10^{-1} and 2.28×10^{-6} g, respectively. By linear interpolation, as performed within AMRAW, the approximate inventory at 160,000 y is 9.04×10^{-2} g. The decay factor becomes simply

$$\text{DECFAC} = 9.04 \times 10^{-2}/3.59 \times 10^{4} = 2.52 \times 10^{-6}$$

and the concentration corrected for decay during transit becomes

$$C = (3.03 \times 10^{-9})(2.52 \times 10^{-6}) = 7.64 \times 10^{-15}\ \mu\text{Ci/cm}^3\ (\text{or Ci/m}^3)$$

still normalized to a 1 Ci release.

The effective plume width, from Eq. 4-84d is $y_w = 2{,}570$ m. The time sub-interval for the 100,000 to 200,000 time increment and $K_d = 1.4 > 1.0$, in accordance with the above discussion, is 20,000 y. Hence, the associated water volume is

$$\text{GNDINC} = 2{,}570 \times 50 \times 1.46 \times 0.15 \times 20{,}000 = 5.63 \times 10^{8}\ \text{m}^3 .$$

Multiplying by the average concentration obtains the activity passing during the internal,

$$\begin{aligned}\text{CRATIO} = (5.63 \times 10^{8})(7.64 \times 10^{-15}) &= 4.30 \times 10^{-6}\ \text{Ci} \\ &= 4.30\ \mu\text{Ci} .\end{aligned}$$

In subprogram TRINP, the above calculation is called for all sub-intervals in the time increment and averaged to obtain the transfer coefficient (A2) for the time increment. If we consider only the sub-interval for illustration, the main program obtains the corresponding activity transported following the 10.1 Ci calculated release as simply

$$(10.1)(4.30 \times 10^{-6}) = 4.34 \times 10^{-5} \text{ Ci} .$$

Also, the main program establishes average ground water concentrations, after accumulating contributions from all releases and adjusting for transfers to other receptors, by dividing the net activity by the associated water volume for the time increment of interest.

(g) Accumulate Concentrations. The product of the Transport-to-Environment portion of the Environmental Model is a matrix, R2TOT, of net total concentrations accumulated for each of the four environmental input receptors, and the land surface deposition matrix, GNDEP, for each zone of the study region, at the end of each time increment considered. This matrix furnishes the environmental concentrations for use by the second part of the Environmental Model which performs the pathway analysis and calculates dose to man.

(h) Sample Calculations. In Section 4.C.1, a sample calculation is given for the probabilistic release to the preliminary environmental input receptor for air during the 400 - 500 y interval as a result of volcanic explosion. The release is 1.1×10^{-5} Ci, representing a quantity, RlJ, released to the air in the immediate vicinity of the repository from either an instantaneous pulse or a slower release over some period of time within the time increment. A sample calculation is now given to illustrate the steps in obtaining the corresponding environmental input concentrations in Zone 2, using data from the base case described in Vol. II, by the Transport-to-Environment part of the Environmental Model.

Figure 4 - 13 uses appropriate portions of Figs. 4 - 8, 4 - 9, and 4 - 10, and illustrates this sample calculation. Consider first, the airborne component. A2 has a value of 1.0 indicating no decay for a time interval coincident with the release interval. Use of an air dispersion code, externally to AMRAW, obtains the integrated concentration per unit release in Ci-y/cm^3-Ci, in various grid subdivisions of Zone 2. The weighted average in the zone in this example is ZONALO = 5.31×10^{-23}, a value input to AMRAW, which represents the average integrated concentration from a diffused unit release pulse moving across

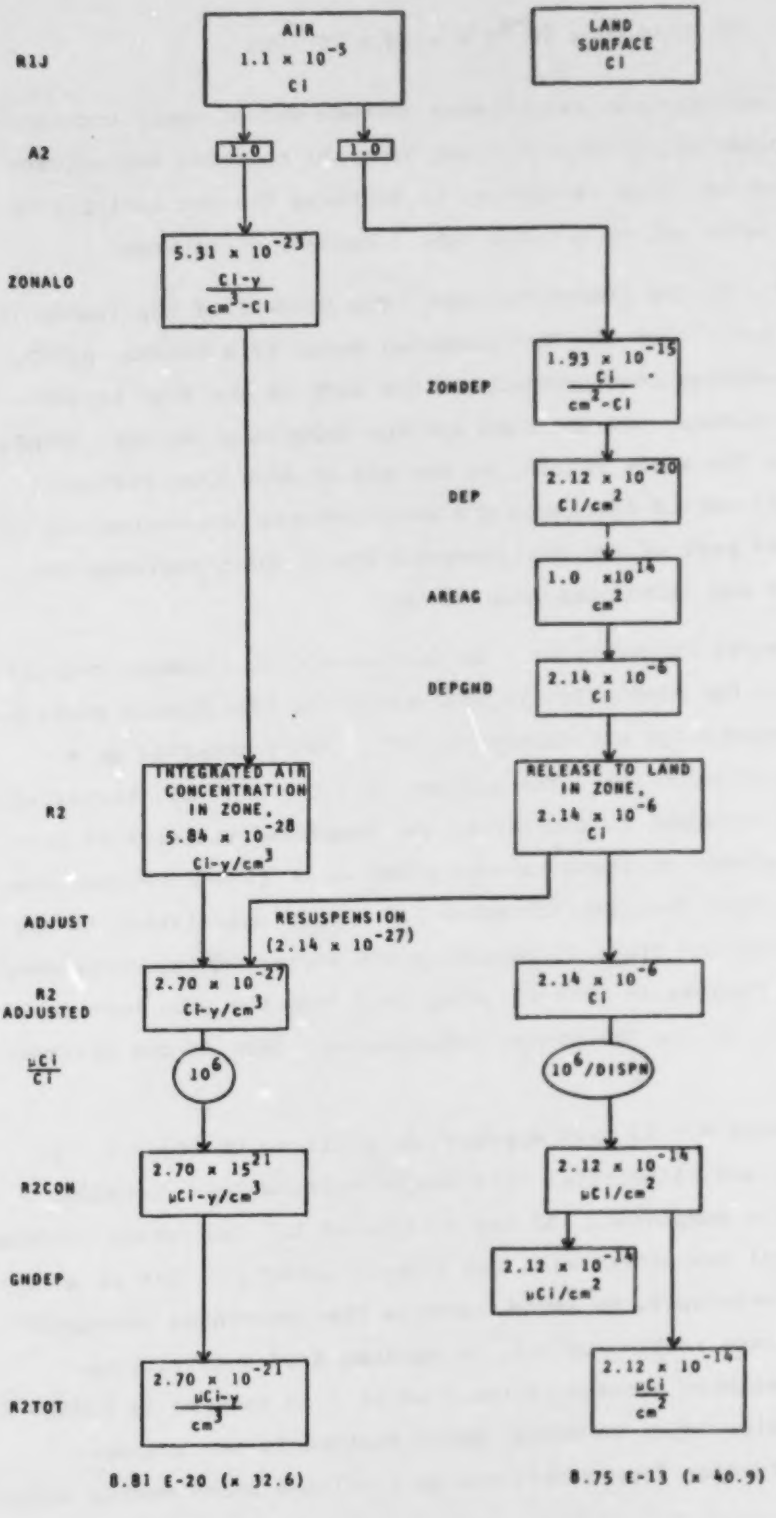


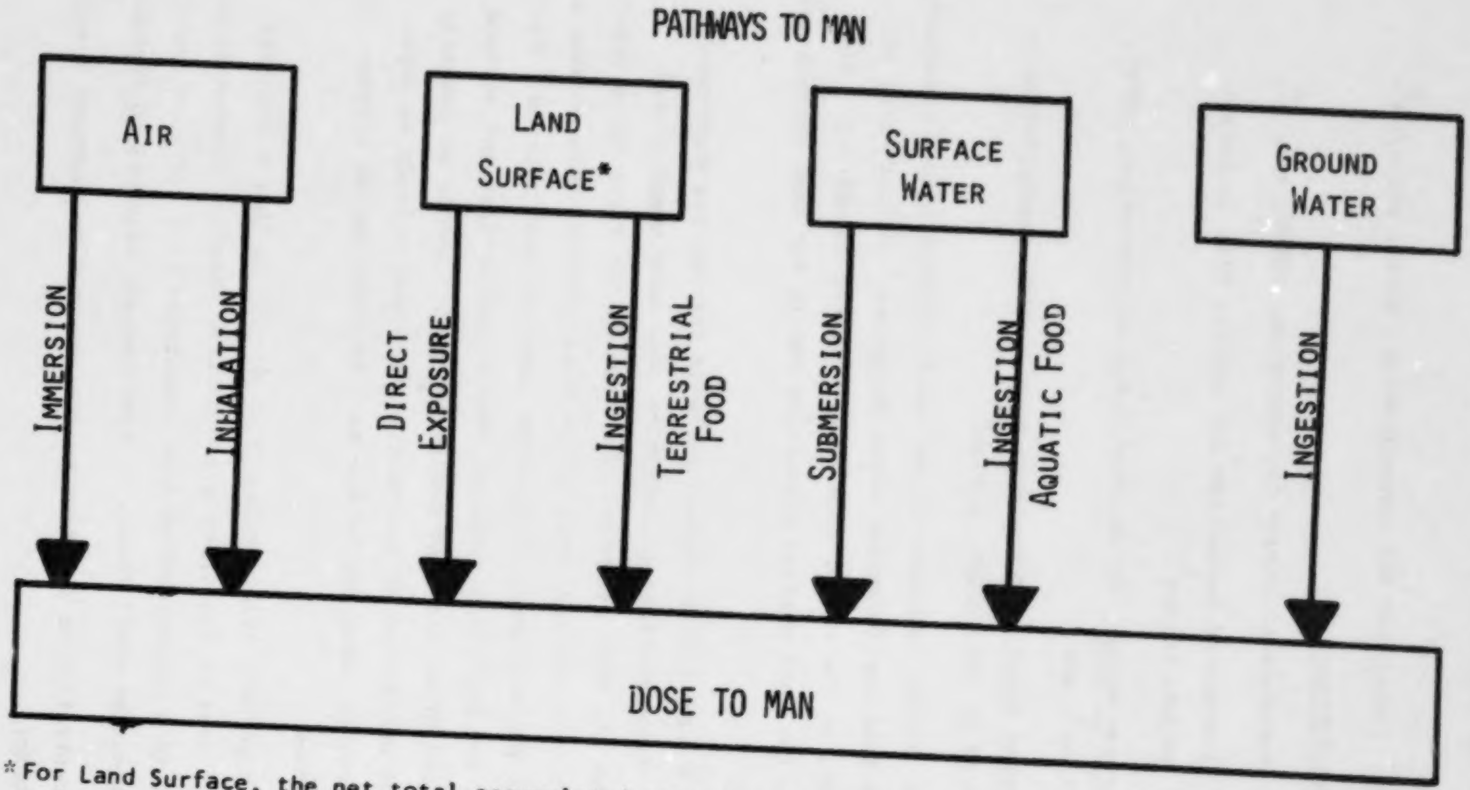
Figure 4-13. Transport to air and land surface environmental input receptors in Zone 2 following volcanic explosion release to air in 400 - 500 y time interval.

the zone. Then, for the given release of R1J = 1.1×10^{-5} Ci, multiplying by A2 and ZONALO obtains the integrated air concentration in the zone of R2 = 5.84×10^{-28} Ci-y/cm^3. Next, this is adjusted for any transfers in from other receptors, in this case as resuspension from land surface. Removal from the air need not be performed at this point since this was taken into account by the external air dispersion code. The resuspension integrated concentration (explained below) is 2.14×10^{-27} Ci-y/cm^3 which when added to the airborne plume component yields a total or "adjusted" value of R2 = 2.70×10^{-27} Ci-y/cm^3. Note in passing that resuspension dominates the air concentration. Multiplying by 10^6 converts units and obtains concentration of R2CON = 2.70×10^{-21} µCi-y/cm^3, also accumulated into the net total air concentration R2TOT = 2.70×10^{-21} µCi-y/cm^3. The term "accumulated" is used here because the code goes through this process for each receptor. For air, however, integrated concentrations do not carry over to a subsequent time increment; the code sets A2 = 0 to accomplish this beyond the present illustration.

Next, consider the ground deposition onto land surface, again referring to Fig. 4 - 13. From air dispersion code calculations, the average deposition per unit release is the input value ZONDEP = 1.93×10^{-15} Ci/cm^2-Ci. Multiplying this by the release R1J = 1.1×10^{-5} Ci obtains ground deposition DEP = 2.12×10^{-20} Ci/cm^2. Multiplying by the area of ground, AREAG = 1.01×10^{14} cm^2 (equal to dispersion area for zone, DISPN) yields the total deposition in the zone, DEPGND = 2.14×10^{-6} Ci, which is carried into the receptor R2. It is here that any other events releasing directly to land surface are added to R2 (omitted from this example for simplicity). The "adjust" step transfers a small fraction of the land surface inventory into the air. This resuspension factor is Ci/cm^3 air concentration per Ci/cm^2 ground concentration. The value input as ADJ1 (E_m in Eq. 3 - 25) is $1. \times 10^{-9}$ cm^{-1}, and it is applied as a step transfer by making ADJ2 (F_m in Eq.4 - 25) sufficiently large (= 20). Then, the integrated resuspension concentration is the zone land surface inventory, R2 = 2.14×10^{-6} Ci, divided by the zone land area, 1.01×10^{14} cm^2 (giving ground concentration), multiplied by the resuspension factor, 1×10^{-9} cm^{-1} (giving air concentration), and multiplied by the duration of the time increment, 100 y, giving the integrated concentration, 2.14×10^{-27} Ci-y/cm^3, which is consistent with the units used for the air receptor. Continuing with the land surface receptor, the small amount of material which continuously cycles through a resuspended status is a neglible removal and the adjusted R2 for land surface is also 2.14×10^{-6} Ci. Multiplication by 10^6 and division by land area DISPN = 1.01×10^{14} cm^2 obtains the concentration, R2CON = 2.14×10^{-14} µCi/cm^2. This concentration is the current time increment deposition, GNDEP, used subsequently for terrestrial food pathway calculations, and is also accumulated into the net total land surface concentration, R2TOT, used subsequently for direct exposure pathway calculations. Residuals from each previous release increment are carried forward (see Fig. 4 - 11 for the steps), considering physical and environmental decay and inter-receptor transfers, and the release increment discussed here is carried forward to subsequent environment time increments. Each such increment makes an additive component to the resuspension air concentration, and the net total, R2TOT, increasing the air and land surface concentrations to larger values than shown here in this sample calculation for one release increment.

Similar calculation steps apply to releases to the other environmental receptors. The deposition to land surface illustrated above is handled in the same way for deposition onto surface water of area, AREAW (see Fig. 4 - 8), giving deposition onto water, DEPWTR, which when divided by the water volume yields the concentration in water, µCi/cm^3. A sample calculation for transport in ground water is included in the earlier Section 4.D.1. (f).(4).

2. Environmental Pathways. The second part of the Environmental Model is the Environment-to-Man Pathways Model, in which pathway analysis is performed and dose equivalent rates to man are calculated. In discussion that follows, frequent use of AMRAW nomenclature is used as an aid in correlating with associated input data which is required. This model is entered for each increment of time with the calculated concentrations for each environmental input receptor. These concentrations,



*For Land Surface, the net total accumulated concentration applies to the Direct Exposure pathway, and current deposition concentration applies to the Terrestrial Food pathway.

Figure 4 - 14. Main environment-to-man pathways.

as determined in the Transport-to-Environment Model discussed previously, are:

1) Air. Integrated air concentration, R2TOT, $\mu Ci\text{-}y/cm^3$,
2) Land Surface.
   a. Accumulated ground concentration, R2TOT, $\mu Ci/cm^2$,
   b. Integrated deposition for current time increment, GNDEP, $\mu Ci/cm^2$,
3) Surface Water. Accumulated water concentration, R2TOT, $\mu Ci/cm^3$, and
4) Ground Water. Accumulated ground water concentration at point of use, R2TOT, $\mu Ci/cm^3$.

The matrix, R2TOT, contains the net total concentrations accumulated for each of the four environmental input receptors, for each zone of the study region, at the end of each time increment considered. Similarly, GNDEP is the land surface deposition matrix for each current time increment.

There are a number of potential pathways through the environment from the input concentrations to radiation dose commitment to man. Fig. 4 - 14 shows the main pathways. For each of the first three receptors, the first main pathway (mode 1) involves external dose sources and the second main pathway (mode 2) involves internal dose sources. For a specific site, the ingestion pathways from ground surface and surface water to food and drink are each subdivided into a number of subpaths for the various categories of terrestrial and aquatic foods as appropriate. In fact, in AMRAW any of the main pathways may be divided into subpaths if needed.

The basic pathway relationship (Fig. 4 - 15) is that a transfer coefficient is used to transform a radioactive material concentration in a receptor to a corresponding dose commitment rate for each specified organ. The transfer coefficient, C, must contain elements to represent:

1) Concentration or dilution to the consumed or exposure quantity (BIOFAC).

2) The amount of exposure or consumption per year (VOLINT).

3) Dose rate conversion per unit of exposure or consumption, for the specified organ (DOSFAC).

Hence, the transfer coefficient is expressed as

$$C = BIOFAC \times VOLINT \times DOSFAC \qquad (4-85)$$

where C and the component factors use a set of units consistent with the environmental concentration to obtain dose or dose rates in the same units for all pathways, to permit summation. Table 4 - 4 details the units for each factor in AMRAW for the main pathways. Any subpaths follow the scheme of the corresponding main pathway.

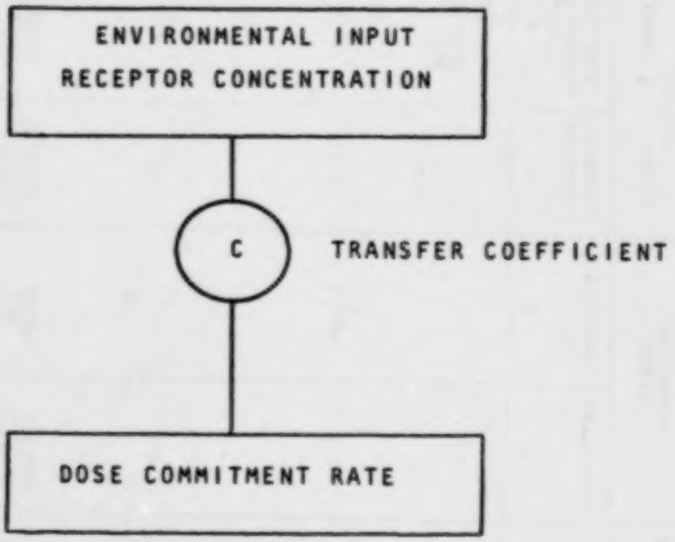


Figure 4 - 15. Basic pathway relationship.

Table 4 - 4. Factors Comprising Environment-to-Man Coefficients

ENVIRONMENTAL INPUT RECEPTOR CONCENTRATION	AIR $\mu Ci\text{-}y/cm^3$ R2TOT		LAND SURFACE $\mu Ci/cm^2$ R2TOT	GNDEP	SURFACE WATER $\mu Ci/cm^3$ R2TOT			GROUND WATER $\mu Ci/cm^3$ R2TOT
Main Pathway	Immersion	Inhalation	Direct Exposure	Ingestion Terrestrial Food*	Submersion	Ingestion Drinking Water	Ingestion Aquatic Food*	Ingestion
Mode	1	2	1	2	1	2	2	1 or 2
Biofactor BIOFAC	---	---	---	$\frac{\mu Ci\text{-}y/g}{\mu Ci/cm^2}$	---	$\frac{\mu Ci/cm^3}{\mu Ci/cm^3}$ (dimensionless)	$\frac{\mu Ci/g}{\mu Ci/cm^3}$	$\frac{\mu Ci/cm^3}{\mu Ci/cm^3}$ (dimensionless)
X								
Consumption, Exposure, or Food Production Rate VOLINT	y/y	cm^3/y	y/y	g/y	y/y	cm^3/y	g/y	cm^3/y
X								
Conversion of Integrated Value to Average Rate 1/DELTE	1/y	1/y	---	1/y	---	---	---	---
X								
Dose Factor DOSFAC	$\frac{mrem/y}{\mu Ci/cm^3}$	$\frac{mrem}{\mu Ci}$	$\frac{mrem/y}{\mu Ci/cm^2}$	$\frac{mrem/y}{\mu Ci/y}$	$\frac{mrem/y}{\mu Ci/cm^3}$	$\frac{mrem/y}{\mu Ci/y}$	$\frac{mrem/y}{\mu Ci/y}$	$\frac{mrem/y}{\mu Ci/y}$
=								
Transfer Coefficient C	$\frac{mrem/y}{\mu Ci\text{-}y/cm^3}$	$\frac{mrem/y}{\mu Ci\text{-}y/cm^3}$	$\frac{mrem/y}{\mu Ci/cm^2}$	$\frac{mrem/y}{\mu Ci/cm^2}$	$\frac{mrem/y}{\mu Ci/cm^3}$	$\frac{mrem/y}{\mu Ci/cm^3}$	$\frac{mrem/y}{\mu Ci/cm^3}$	$\frac{mrem/y}{\mu Ci/cm^3}$
Dose Rate	mrem/y#	mrem/y#	mrem/y	mrem/y#	mrem/y	mrem/y	mrem/y	mrem/y

*Food pathways divide into sub-paths (not shown).

#Transfer coefficient yields average dose commitment rate during time interval in which integrated dose commitment occurs.

The air pathways involve integrated air concentration and the terrestrial food pathway involves integrated food concentrations. These are converted to average dose rates during a time increment by dividing by the length of the time increment, as shown in Table 4 - 4 to provide consistent units for summation with other pathways which directly produce average dose rates. The use of dose rates instead of the corresponding integrated doses during each time increment permits inspection of output tables for trends where the size of time increments varies.

(a) Integrated Food Concentrations. Before describing the component factors of the transfer coefficient, a discussion of food concentrations will be helpful. If there is a uniform and continuous deposition rate, equilibrium concentrations of each radionuclide are approached in various components of the terrestrial environment and in terrestrial foods. Following an acute deposition, there is a transient response for food concentrations. Fig. 4 - 16 illustrates the response of concentration of Sr-90, in μCi/g, in above-surface crops, milk and meat following a unit acute deposition of 1 $\mu Ci/cm^2$. These curves are typical in general characteristics to those for other radionuclides. Above-surface-food crops have a maximum concentration initially, due to foliar deposition, followed by decay through wash-off. Milk and beef are initially at zero and increase with contaminated food intake. Movement of radionuclides down through the soil horizons eventually removes them from further intake, and biological elimination processes produce an exponential reduction of the concentrations in foods. The peak concentration for the example illustrated occurs at approximately 2d for milk and at 50d for meat. Appendix B presents a detailed analysis of the equations from the TERMOD code [Kℓ76] and the food concentration responses for several radionuclides. The area under each curve for a given radionuclide, integrated in terms of years, represents the integrated food concentration, μCi-y/g. The analysis (Appendix B) shows that the time constants for transfer downward from foliage through soil horizons to the soil sink (beyond root zone) override the significance of physical half-life such that virtually complete integration is attained in less than five years, even for the longest half-lives. Therefore, as AMRAW is typically implemented with time increments greater than five years, a calculated release accumulated during one release time increment, treated

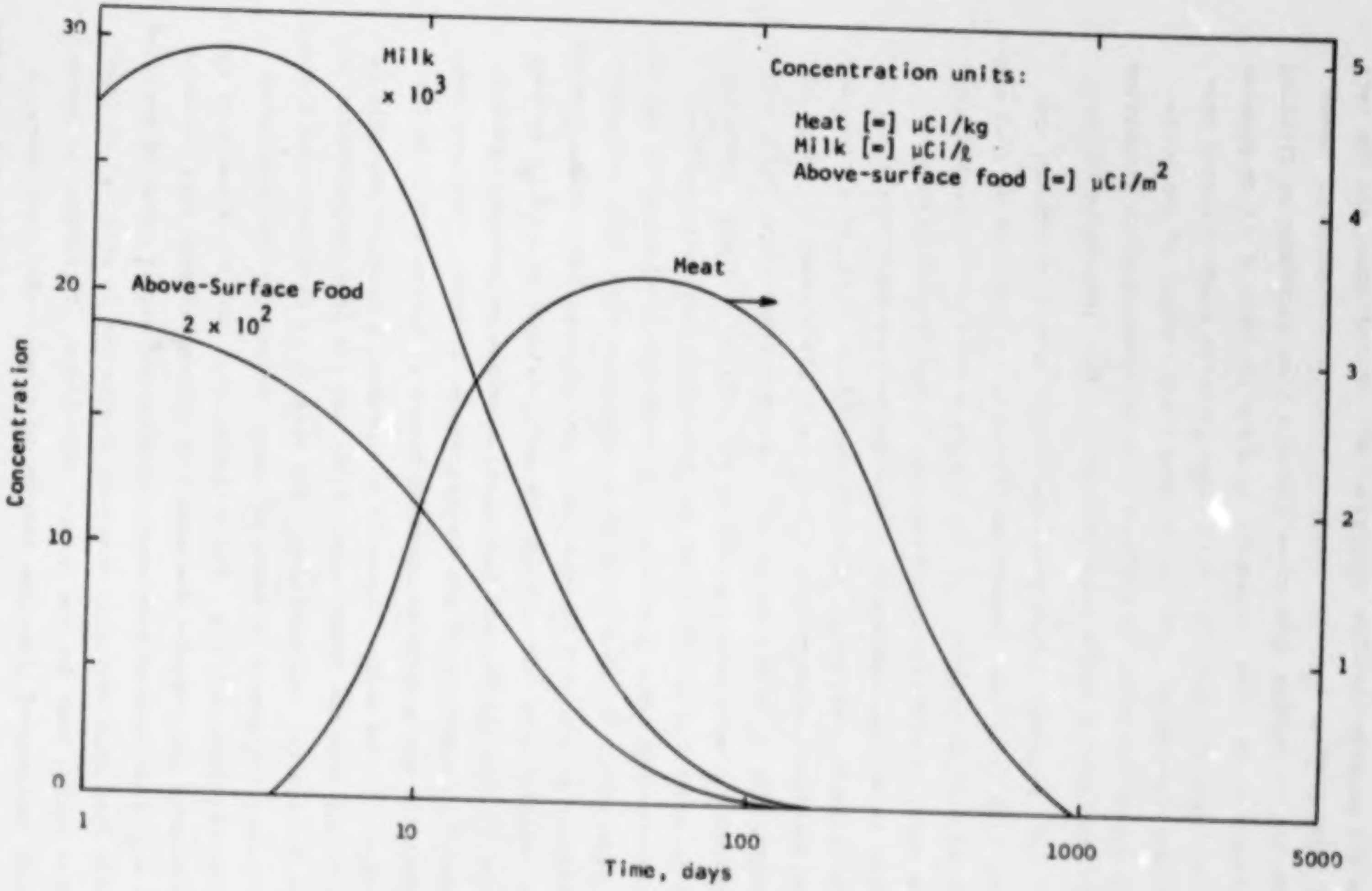


Figure 4 - 16. Response of concentration of Sr-90 in food to unit deposition.

as an acute release, results in terrestrial food consequences which are completed within the following environmental time increment. It is advantageous to base the terrestrial food on the concept of integrated concentration following an acute deposition. There is an equivalence of the ratio of the equilibrium concentration in food (μCi/g) to a unit continuous surface deposition rate ($\mu Ci/cm^2$-d) with the ratio of the integrated concentration in the food (μCi-d/2) to a unit acute surface deposition ($\mu Ci/cm^2$). This equivalence provides for a simple application of terrestrial code output (converted from unit of day to year) to obtain integrated concentrations.

(b) Local Dose and Nonspecific Dose. Some of the pathways (or subpaths) discussed above have a direct effect on populations within each geographic zone considered. These are: immersion in air, inhalation, exposure to contaminated land surface, and submersion in and ingestion of contaminated water. Dose to man by organ resulting from these pathways, in millirems per year per individual, is collected as "local dose rate" for each zone. All of the pathways concerned with production of agricultural commodities produce effects which are not localized to the zones in which the food is produced; most of the food is exported. Dose to man by organ resulting from these pathways is collected as manrems of population dose per year as "nonspecific dose rate." Accordingly, for this last category, food production rates are involved instead of individual consumption rates. Data input to AMRAW for each subpath includes a flag which identifies the dose category to which the calculations accrue.

(c) Component Factors for Transfer Coefficient. The three factors: BIOFAC, VOLINT, and DOSFAC, are obtained from output tabulations by existing computer codes or other sources and supplied to AMRAW as input data for each subpath, along with data designating the number of subpaths under each receptor and mode (see Table 4 - 4) and designations of dose category.

The first factor, BIOFAC, expresses the concentration or integrated concentration in food and drink per unit concentration in the associated environment. For terrestrial food, this is the integrated concentration, μCi-y/g per unit of acute deposition, $\mu Ci/cm^2$, as discussed previously. Codes such as TERMOD [Kl76] or FOOD [Ba76] may be used to perform calculations for preparation of AMRAW input.

For aquatic foods, BIOFAC is simply the nuclide-dependent bioaccumulation factors for each class of aquatic food considered, μCi/g in the food per $\mu Ci/cm^3$ of water concentration. Tabulations such as those by Thompson et al. [Tp72] and ORNL [ORNL75] provide this information. For ingested water BIOFAC is unity (dimensionless), although it could be set at less than unity if water treatment may be assumed.

Contamination of meat and milk from contaminated drinking water uses BIOFAC obtained for each radionuclide as the product of the stable element transfer factor (meat or milk as appropriate) and the water consumption rate. With unit conversions this becomes $(\mu Ci/g)/(\mu Ci/cm^3)$, as with aquatic foods in Table 4 - 4.

The second factor, VOLINT, expresses the consumption, exposure or food production rate for each zone and subpath. For immersion in air or water, or direct exposure to contaminated land surface, VOLINT is the average fraction of a year during which individuals are so exposed. For inhalation, the value is respiration rate, cm^3/y, and for ingestion of water by people it is the intake rate, cm^3/y. As explained above, pathways concerned with production of agricultural commodities produce effects collected as "nonspecific dose rates." Accordingly, VOLINT for these paths are food production rates, g/y.

The last factor, DOSFAC, is the dose commitment conversion factor for each radionuclide, organ, and exposure mode combination. External exposure modes are air immersion, land surface direct exposure, and surface water submersion. Internal exposure modes are air inhalation, and ingestion of food or drink. Dimensions are as shown in Table 4 - 4. Codes such as EXREM III [Tr73, Kℓ76] and INREM [Kℓ75, Kℓ76] provide dose conversion factors for external and internal sources, respectively. AMRAW is presently dimensioned to handle up to eight organs, including total body.

(d) Operation of Code. Each subpath is provided with a flag to denote whether results are to be accumulated as local or as nonspecific dose rates. For each time increment, zone, and organ, the AMRAW main program: (1) considers each of the four environmental receptors in turn, (2) calls subroutine TRMAN to obtain and return the summation transfer coefficient C for all subpaths associated with the respective receptor,

contributing to local dose rate, and then calculates the corresponding dose equivalent rate, and (3) repeats for nonspecific dose rates. This process is repeated for all organs for the given zone, for all other zones, and for all other time increments. The nonspecific dose category accumulates from all zones.

It should be noted that the Environment-to-Man Pathways Model is fully dependent upon input data determined by other external models and codes. The model within AMRAW serves to perform the arithmetic for the many combinations of parameters to produce the output dose rate matrices. The dose rates calculated in the environmental model are the last items of output by AMRAW-A. They are subsequently entered into AMRAW-B, the economic model, where consequences of dose are evaluated, beginning with the application of health effect incidence rate factors for each organ dose rate.

(e) Sample Calculations. In Section 4.D.1, a sample calculation is given which obtains environmental input concentrations of Sr-90 for air and land surface receptors in Zone 2, associated with probabilistic volcanic release during the 400 - 500 y interval. Continuing, using data from the base case described in Vol. II, a sample calculation is now given to illustrate the Environment-to-Man Pathways Model part of the Environmental Model (Fig. 4 - 14).

Table 4 - 5 shows the calculation sequence for the air and land surface receptors, for one zone (Zone 2) and one organ (total body). This table is the applicable portion of Table 4 - 4, with typical numerical values (see Vol. II) indicated. As pointed out in the earlier Transport-to-Environment sample calculations, the receptor concentrations shown represent only the quantities from the sample release increment; in AMRAW, residuals from previous release increments are accumulated, increasing the land surface total (R2TOT), and the corresponding resuspension increases air concentration (R2TOT). In Table 4 - 5, modes 1 and 2 under each receptor represent external and internal main pathways, respectively. There is one subpath under each main pathway for this example. For other zones, additional terrestrial food subpaths (above-surface-crops, milk, and hay-fed-meat) are included under mode 2 for land surface.

Table 4-5. Sample Calculation, Environmental Pathways in Zone 2, Total Body Dose Rates from Sr-90 Following Volcanic Explosion Release to Air in 400 - 500 y Time Interval

	AIR		LAND SURFACE	
Environmental Input Receptor Concentration	R2TOT = 2.7×10^{-21} $\mu Ci\text{-}y/cm^3$		R2TOT = 2.1×10^{-14} $\mu Ci/cm^2$	GNDEP = 2.1×10^{-14} $\mu Ci/cm^2$
Main Pathway	Immersion	Inhalation	Direct Exposure	Ingestion Terrestrial Food
Mode	1	2	1	2
Subpath	Immersion	Isolation	Direct Exposure	Meat (Range Fed)
BIOFAC	---	---	---	$0.53 \frac{\mu Ci\text{-}y/g}{\mu Ci/cm^2}$
x				
VOLINT	1.0 y/y	7.3×10^{9} cm^3/y	0.4 y/y	1.2×10^{10} g/y
x				
1/DELTE	1/100 y	1/100 y	---	1/100 y
x				
DOSFAC	$0.0 \frac{mrem/y}{\mu Ci/cm^3}$	$1.8 \times 10^{3} \frac{mrem}{\mu Ci}$	$0.0 \frac{mrem/y}{\mu Ci/cm^2}$	$1.7 \times 10^{2} \frac{mrem/y}{\mu Ci/y}$
=				
Transfer Coefficient C	$0.0 \frac{mrem/y}{\mu Ci\text{-}y/cm^3}$	$1.3 \times 10^{11} \frac{mrem/y}{\mu Ci\text{-}y/cm^3}$	$0.0 \frac{mrem/y}{\mu Ci/cm^2}$	$1.1 \times 10^{10} \frac{mrem/y}{\mu Ci/cm^2}$
Dose Rate	0.0 mrem/y	3.5×10^{10} mrem/y	0.0 mrem/y	2.3×10^{-4} mrem/y

A subroutine in AMRAW (TRINP) calculates the transfer coefficients, C, for each mode under each receptor (for given radionuclide, zone, organ, and duration of environmental time increment). The main program then multiplies the respective receptor concentrations at the time of interest by the transfer coefficient values to obtain dose commitment rates. To illustrate the calculation of C, consider the subpath for meat in Table 4 - 5 (last column). Note that C = BIOFAC x VOLINT x DOSFAC/DELTE. Here, BIOFAC is the integrated concentration of Sr-90, (μCi-y/2)/(μCi/cm^2), in range-fed meat animals following a unit deposition of Sr-90 on the land surface. VOLINT is the total meat production rate, g/y, for the zone considered. The quantity represents mass added during grazing in the zone and does not include meat added in feed lots after export from the contaminated zone. With use of total meat production, the subsequent dose rate is routed to the nonspecific dose category by input of the appropriate flag values in AMRAW. If local dose rate to an individual is preferred for ingestion pathways, the individual meat consumption rate is used for VOLINT and the appropriate route flag is used. DOSFAC is the dose conversion factor for dose commitment for ingestion, mrem/μCi, or rates, (mrem/y)/(μCi/y). DELTE is the duration of the time increment, used for conversion from an integrated value to an average value. The subroutine (TRMAN) calculation of C accumulates for all subpaths under a mode and does not preserve component subpaths nor intermediate values for a given subpath. It is of interest here to trace the intermediate values implied by the calculation sequence. First, multiplying the ground deposition quantity, 2.1 x 10^{-14} μCi/cm^2, by BIOFAC obtains the integrated concentration in the meat, 1.1 x 10^{-14} μCi-y/g. Then, multiplication by VOLINT obtains the total contamination activity in meat produced during the time increment, 1.3 x 10^{-4} μCi. Division by DELTE converts to the average rate, 1.3 x 10^{-6} μCi/y. Finally, multiplication by DOSFAC produces the dose rate, 2.3 x 10^{-4} mrem/y. When routed to nonspecific dose rate, due to use of total production rate, the result is 2.3 x 10^{-4} millimanrem/y, converted to 2.3 x 10^{-7} manrem/y. It should be noted that the location of the division by DELTE in this sequence has no effect or the numerical result. If the division is left until the end, it can be shown that the result after multiplying by DOSFAC is integrated dose, 2.3 x 10^{-2} mrem, which when divided by DELTE becomes dose rate, 2.3 x 10^{-4} mrem/y, as before.

The other subpaths in Table 4 - 5 are similarly calculated. In this example, since Sr-90 has no gamma emission, there is no external mode exposure (DOSFAC = 0.0). Factors which do not apply are assigned a value of unity within AMRAW. In the main program, the dose rates for each mode under each receptor are routed to the appropriate category (local or nonspecific) in accordance with routing flags. As indicated above, nonspecific dose rates to the population become stated as man-rems/y. Vol. II discusses the sources of input data for the several factors for an implementation example.

E. MATHEMATICAL SUMMARY OF MODEL (G. M. McNERNEY)

This section gives a mathematical development of the portion of the Waste Management Systems Model upon which the AMRAW-A computer code is based. It is necessary for computational purposes that all of the independent and dependent variables be discrete. However, a continuous representation with the transformations $\Delta t \rightarrow dt$, $\Delta x \Delta y \rightarrow dxdy$ of the equations involved are given first. This facilitates an easier understanding of the model by replacing subscripts with continuous variables. After the continuous representation is discussed, the corresponding discrete equations are given as they appear in the AMRAW code.

1. Continuous Representation. The variables and subscripts have the following meanings: τ is the variable time, t is a release time of radionuclide from the waste site to the Preliminary Environmental Receptors, T is time of interest for population doses, $\vec{r}$ is a space variable in the rectangular coordinate system (x, y, z) in which the origin of coordinates is the land surface directly above the waste site, i is a subscript denoting a release event, j is a subscript for the environmental receptor which is of current interest, and m is a subscript for any environmental receptor other than j. Generally, the space variable representation may be considered two-dimensional since we are mostly concerned with concentrations on the land or in surface water.

The starting point of the computation is the introduction through data statements of the quantity of the radionuclide in grams as a function of time, X(t). For simply decaying nuclides [My67] (i.e., no radioactive parents)

$$X(t) = X(0) \exp(-\lambda t) \qquad (4-86)$$

where X(0) is the amount of the nuclide at some reference time, and the radioactive decay constant, λ, is related to the half-life, $t_{1/2}$, by $\lambda = .693/t_{1/2}$. If ω_o is the specific activity in Ci/g of the particular radionuclide of interest, then

$$Y(t) = X(t) \cdot \omega_o$$

is the radioactivity in Ci at time t for the radionuclide.

Nuclides in decay chains, like many transuranic isotopes, have complex simultaneous buildup and decay. The time-dependent quantities for these nuclides have been previously computed in the ORIGEN computer code, and are provided to the AMRAW code for each time t in data statements. A radiodecay factor DC(t,T) between two times t, and T may be expressed as the ratio of nuclide quantities for the two times. For nuclides released at time t, the subsequent distribution and radioactive decay is computed by means of the transfer coefficient A2(t, T, $\vec{r}$), to be discussed below.

The next phase of the computation relates to the release model which determines release mechanisms moving the nuclide from the repository to the preliminary environmental receptors.

A versatile method for computation with release mechanisms is to introduce a probability density function $P_{ij}(t)$ which represents the probability of release by release mechanism i to environmental receptor j during the time interval (t-dt, t). The resulting generality allows computations to be made either with acute release from mechanism i by setting $P_{ij}(t)$, for example, equal to the delta function $\delta(t - t')$ for the appropriate time t', or with chronic release by setting $P_{ij}(t)$ equal to the constant function, step function, ramp function or exponential function which is available in the AMRAW code. A suddenly occurring event which is followed by continuing release, such as an earthquake, makes use of the step function and a suddenly occurring but brief event such as meteorite impact may be expressed by use of the delta function. On the other hand, consideration of contamination from release following an event such as ground surface erosion involves no release until enough time has passed for denuding to occur; the shortest time requires the most rapid erosion and has the least probability of occurrence while there is an increasing probability of lower erosion rates (denuding in longer times). This may be represented by the linearly increasing ramp function.

Let $A1_{ij}(t)$ represent the transfer coefficient for transfer from the repository to receptor j by release mechanism i. This coefficient depends upon the physical properties of the particular release event and receptor. The $A1_{ij}(t)$ and $P_{ij}(t)$ are both computed in subroutine FAULT for each instance. Information is provided to subroutine FAULT by input data from externally computed data values. Consequently, the following result

$$\left\langle Al_j(t) \right\rangle = \sum_i P_{ij}(t) \cdot Al_{ij}(t) \qquad (4\text{-}87)$$

gives the expectation value for the transfer coefficient from all release events at time t to receptor j.

Since we are considering the contribution to population doses from each different environmental receptor in turn, the subscript j may henceforth be dropped for simplification except where confusion is possible. It should be noted here that the four receptors are treated slightly different. This is due to deposition onto land surface and surface water of material which is released to air. This is discussed in detail in Section 4.D. The following discussion is for the receptor ground water as an illustration; the other receptors are handled by adding appropriate terms.

Let $Z(\vec{r})$ be a dimensionless function which gives the fraction of released nuclide deposited at position $\vec{r}$. In AMRAW, $Z(\vec{r})$ is a discrete function for the zones, giving the fraction of the release which ends up in each zone. This zone allocation factor involves external calculations with air and land dispersion models. For ground water the factor serves to indicate delivery via a ground water path to a given geographic zone. The space dependent source term is then

$$q(t, \vec{r}) = Y(t) \cdot \left\langle Al(t) \right\rangle \cdot Z(\vec{r}) \qquad (4\text{-}88)$$

giving the activity in Ci at position $\vec{r}$ from nuclide released at time t. The sum over release events is finite; therefore, q can be considered to be an expected value. Similarly, all functions developed in the following sequence of equations (except G_m in Eq. 4-89) can also be considered to be expected values. However, in AMRAW, the summation occurs at the step represented by Eq. 4-87. Therefore, the expected value symbol is omitted from the subsequent equations.

The next step of the calculation involves transfer from the receptor of interest at release time t to population dose time T, and to the receptor of interest from other receptors. The introduction of two transfer coefficients, A1 (already discussed) and A2, requires further explanation. Each environmental input receptor is a volume of air or water, or area of land surface. Some potential release events may provide initial depositions which serve as concentrations at environmental input receptors. However, other potential release events may involve secondary distribution processes. An example is leaching of a waste deposit process by circulating ground water. This release process requires a geologic faulting event to cause a major non-healing fracture through the deposit, coupled with the presence of ground water, for leaching to occur. However, particularly with deep burial, release by leaching to ground water is not in itself a release to the environment. In addition, transport is required before contamination concentrations accrue in an aquifer contributing to the biosphere. The use of the two transfer coefficients, A1 and A2, then provides the flexibility to cope with the physico-chemical aspects of such two-stage release and transport processes. Section 3.D. provides a detailed description of these coefficients.

The coefficient $A2_j(t, T, \vec{r})$ is a time transfer coefficient, accounting for radioactive and environmental decay occurring between release time t and population dose time T. In addition, the coefficient can account for special transport processes within one receptor. The coefficients A2 are computed from AMRAW input data in subroutine TRINP. For the receptors air, surface water, and land surface, the calculations are done completely within this subroutine. For ground water, subroutine TRINP calls function CRATIO for ground water transport calculation of concentration ratios.

Some quantity of the nuclide enters the receptor j from the other receptors, and it is thus necessary to add terms to the $A2_j(t, T, \vec{r})$ to account for these processes. Two sets of functions $E_m(\vec{r})$ and $F_m(\vec{r})$ account for transfer between receptor terms and are provided to the AMRAW code as input data. $E_m(\vec{r})$ is the maximum fraction of the nuclide in receptor m which can be transferred to receptor j. $F_m(\vec{r})$ gives the fractional rate of transfer of the nuclide from receptor m to receptor j.

Then, the transfer fraction term of nuclide from receptor m to receptor j is given by

$$G_m(t,\ T,\ \vec{r}) = E_m(\vec{r})\left[1 - \exp\left(-F_m(\vec{r}) \cdot \delta\right)\right] \tag{4-89}$$

where $\delta = \int d\tau$ (range of integration is period during which transfer is considered).

If rapid transfer is expected, $F_m(\vec{r})$ is given a large value, while for slow transfer, $F_m(\vec{r})$ takes a smaller value.

Thus, in the following equation,

$$H(t,\ T,\ \vec{r}) = \sum_{m\neq j} G_m(t,\ T,\ \vec{r}) \cdot A2_m(t,\ T,\ \vec{r}) \cdot q_m(t,\ \vec{r}) \tag{4-90}$$

$H(t,\ T,\ \vec{r})$ gives the total transfer term to receptor j from the other receptors m. The corresponding loss from receptor j, at $\vec{r}$, to other environmental receptors during the period t to T is given by

$$L_j(t,\ T,\ \vec{r}) = \sum_{m\neq j} G_{j\to m}(t,\ T,\ \vec{r}) \cdot A2_j(t,\ T,\ \vec{r}) \cdot q_j(t,\ r). \tag{4-91}$$

The quantity

$$S(t,\ T,\ \vec{r}) = q(t,\ \vec{r}) \cdot A2(t,\ T,\ \vec{r}) + H(t,\ T,\ \vec{r}) - L_j(t,\ T,\ \vec{r}) \tag{4-92}$$

is then the final source term representing the total activity at $\vec{r}$ in receptor j at time T due to release at time t.

Introducing the local dispersion factor $DS(\vec{r})$, which is reciprocal area or volume as appropriate, provides concentration values for uniform dispersion of the radionuclide deposited within a zone. The following relation results

$$R(t,\ T,\ \vec{r}) = S(t,\ T,\ \vec{r}) \cdot DS(\vec{r}), \tag{4-93}$$

where $R(t,\ T,\ \vec{r})$ is the activity in Ci/cm^2 or Ci/cm^3 at time T and position $\vec{r}$ due to release in the time interval (t - dt, t).

Integrating over all release times prior to T, Eq. 4 - 93 becomes

$$RT(T, \vec{r}) = \int_{t_o}^{T} R(t, T, \vec{r})dt = DS(\vec{r}) \cdot \int_{t_o}^{T} S(t, T, \vec{r}) \cdot dt. \quad (4\text{-}94)$$

Here, $RT(T, \vec{r})$ corresponds either to the total activity per unit volume for ground water or surface water, activity per unit area for land surface, or integrated activity for air, at time T and position $\vec{r}$ due to all previous release events.

The coefficients for transfer from environmental receptors to population dose are now considered. Pathway analysis considers two categories of pathways from environmental concentrations to population dose: 1) local dose rates for persons in the vicinity of position $\vec{r}$, and 2) nonspecific dose rates to persons at undefined locations from foods grown in the vicinity of position $\vec{r}$. The coefficient $A31(\vec{r})$ is the local dose transfer coefficient, and $A32(\vec{r})$ is the nonspecific dose transfer coefficient. These two coefficients are discussed in Section 4.D. and are computed in subroutine TRMAN. The dependence of A31 and A32 on various organs of the body is suppressed here but is included in the complete calculations.

The local dose rate at time T is then

$$M1(T, \vec{r}) = RT(T, \vec{r}) \cdot A31(\vec{r}) \quad (4\text{-}95)$$

and the nonspecific dose rate at time T is

$$M2(t) = \iint RT(T, \vec{r}) \cdot A32(\vec{r}) \cdot d\vec{r}. \quad (4\text{-}96)$$

The quantities M1 and M2 given here represent population dose rates only from receptor j for a specific radionuclide. The total dose rates are obtained by summing over all receptors and radionuclides. The double integral in M2 is to obtain the total contribution to the nonspecific dose from all spatial locations.

2. Discrete Representation. The discrete equations may be obtained from the continuous equations by replacing the continuous variables with superscripts and subscripts, and integrals with finite sums. To prevent

confusion, time-dependence is represented by superscripts, and all other independent variables are represented by subscripts. Release time t is labeled by the superscript α, and population dose time T is likewise labeled by the superscript β. The space dependence, or the variable $\vec{r}$ is replaced by zone dependence denoted by the subscript k. It should be pointed out that the time increments Δt^{α} and Δt^{β} are not uniform in the AMRAW calculations and the superscripts are thus necessary. The discrete form of $d\vec{r}$ is not needed; all other subscripts retain their original meaning.

The final objective is to represent Eqs. 4 - 95 and 4 - 96 in the continuous representation in discrete notations. The resulting expressions explicitly contain all the calculations in the AMRAW code for ground water, except the transfer between receptor calculations. As mentioned in the discussion of the continuous representation, the other receptors are slightly more complicated and need minor modifications.

The quantity of radionuclide assumed available for release in the time increment Δt^{α} is the average of the radionuclides available at time t and time $t^{\alpha-1}$. Thus $X^{\alpha} = \frac{1}{2}\,[X(t^{\alpha}) + X(t^{\alpha-1})]$, and the activity corresponding to Eq. 4 - 86 for the continuous representation is

$$Y^{\alpha} = X^{\alpha} \cdot \omega_{o}. \tag{4-97}$$

The probability density function at release time t^{α} is P^{α}_{ij}, and the first transfer coefficient is Al^{α}_{ij}.

Thus, corresponding to Eq. 4 - 87,

$$\left\langle Al^{\alpha}_{j} \right\rangle = \sum_{i} P^{\alpha}_{ij}\, Al^{\alpha}_{ij} \tag{4-98}$$

is the expectation value for the transfer coefficient.

The term Z_{jk} is the zone-dependent factor which gives the fraction of the amount released to receptor j that ends up in that receptor for Zone k. The zone-dependent source term is then, corresponding to Eq. 4 - 88,

$$q^{\alpha}_{jk} = Y^{\alpha} \cdot \left\langle Al^{\alpha}_{j} \right\rangle \cdot Z_{jk}. \tag{4-99}$$

In the continuous case, the second transfer coefficient was introduced as a given function $A2(t, T, \vec{r})$. In the discrete case, the computation of the second transfer coefficient is rather complicated, and its representation as a continuous function needs some justification.

Let $A2^{\alpha\beta}_{jk}$ be the discrete analog of $A2_j(t, T, \vec{r})$. Then $A2^{\alpha\beta}_{jk}$ is determined as follows. A quantity, $A^{\alpha\beta}_{jk}$, is computed in subroutine TRINP for each population dose time greater than or equal to the release time $\left(T^\beta \geq t^\alpha\right)$ For the case where population dose time equals the release time $\left(T^\beta = t^\alpha\right)$,

$$A2^{\alpha\alpha}_{jk} = A^{\alpha\alpha}_{jk}.$$

Subsequently, $A2^{\alpha\beta}_{k}$ is defined recursively by

$$A2^{\alpha\beta}_{jk} = A2^{\alpha\beta-1}_{jk} \cdot A^{\alpha\beta}_{jk},$$

or, in general,

$$A2^{\alpha\beta}_{jk} = \prod_{\alpha\leq\gamma\leq\beta} A^{\alpha\gamma}_{jk},$$

where $\prod_{\alpha\leq\gamma\leq\beta}$ represents product summation and γ ranges from α to β. Thus, for example,

$$A2^{14}_{jk} = \prod_{1\leq\gamma\leq4} A^{1\gamma}_{jk} = A^{11}_{jk} \cdot A^{12}_{jk} \cdot A^{13}_{jk} \cdot A^{14}_{jk}.$$

This computational form was chosen since it can be easily used to handle radioactive decay.

Now, letting $E_{mj}(\vec{r})$, $F_{mj}(F)$, $G_{mj}(t, T, \vec{r})$ and $DC(t, T)$ be replaced by E_{mjk}, F_{mjk}, $G^{\alpha\beta}_{mjk}$, and $DC^{\alpha\beta}$, respectively, the transfer to receptor j from receptor m corresponding to Eq. 4 - 89 is given by

$$G^{\alpha\beta}_{mjk} = E_{mjk} \left|1 - \exp\left(-F_{mjk} \cdot \Delta T^\beta\right)\right|, \qquad (4\text{-}100)$$

and, corresponding to Eq. 4 - 90,

$$H^{\alpha\beta}_{jk} = \sum_{m\neq j} G^{\alpha\beta}_{mjk} \cdot A2^{\alpha\beta}_{mk} \cdot q^{\alpha}_{mk} \qquad (4\text{-}101)$$

is the total transfer to receptor j from all other receptors.

The quantity

$$L^{\alpha\beta}_{jk} = \sum_{m\neq j} G^{\alpha\beta}_{jmk} \cdot A2^{\alpha\beta}_{jk} \cdot q^{\alpha}_{jk}$$

is the corresponding term representing transfer from receptor j up through time T^{β} to all other receptors.

The final source term corresponding to Eq. 4 - 92 is then

$$S^{\alpha\beta}_{jk} = q^{\alpha}_{jk} \cdot A2^{\alpha\beta}_{jk} + H^{\alpha\beta}_{jk} - L^{\alpha\beta}_{jk}. \qquad (4\text{-}102)$$

The local dispersion factor depends on both the zone and the receptor, and is thus represented by DS_{jk}.

So, corresponding to Eq. 4 - 93,

$$R^{\alpha\beta}_{jk} = S^{\alpha\beta}_{jk} \quad DS_{jk} \qquad (4\text{-}103)$$

is the activity at time T^{β} in Zone k due to release in the time interval Δt^{α}.

Summing over all release times up to population dose time T^{β}, corresponding to Eq. 4 - 94,

$$RT^{\beta}_{jk} = \sum_{\alpha\leq\beta} R^{\alpha\beta}_{jk} = DS_{jk} \cdot \sum_{\alpha\leq\beta} S^{\alpha\beta}_{jk} \cdot \Delta t^{\alpha} \qquad (4\text{-}104)$$

is the total activity at time T in Zone k.

If the population dose rate transfer coefficients are represented by $A31_j$ and $A32_j$, the resulting local dose rates are given by

$$M1^{\beta}_{jk} = RT^{\beta}_{jk} \cdot A31_j, \qquad (4\text{-}105)$$

and the resulting nonspecific dose rates corresponding to Eq. 4 - 96 are

$$M2^{\beta}_{j} = \sum_{k} RT^{\beta}_{jk} \cdot A32_j. \qquad (4\text{-}106)$$

These last two equations represent the final output of AMRAW-A.

CHAPTER 5

DESCRIPTION OF AMRAW-A COMPUTER CODE

The AMRAW Code is written in Fortran IV language. The two parts of the codes are: 1) AMRAW-A which contains the Source Term, the Release Model, and the Environmental Model, and 2) AMRAW-B which contains the Economics Model. They are being run separately but may be joined if desired. There is an advantage to running the first part independently to determine sensitivity of environmental concentrations and dose rates to variations in input. Similarly, there is an advantage to running the economic model independently to study the response to varied economic parameters. User's manuals are Volume IV for AMRAW-A and Volume VI for AMRAW-B. This chapter provides a brief description of AMRAW-A; similarly, Chapter 6 in Volume V describes AMRAW-B.

The present dimensioning of AMRAW-A is as follows:

1) Radionuclides: 25.

2) Environmental receptors: 4, designated by programming as Air, Land Surface, Surface Water, and Ground Water.

3) Release Model events: 9 events or event combinations under each of the 4 environmental receptors. Each may be input with up to 4 component factors. Each of these factors may be flagged for type of function (constant, step, ramp, exponential, or delta) and specified by three appropriate function parameters.

4) Environmental pathways: 2 main pathways (modes) are programmed for each environmental receptor. Dimensioning provides for up to 6 subpaths for each receptor (each mode under a given receptor is divided into the same number of subpaths).

5) Geographic zones: 8.

6) Human organs: 8. Typically, one of these is total body, but there is no restriction.

7) Time increments: 50.

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With this dimensioning, the code runs with 256 k bytes of core storage, 10 cylinders (1459 k bytes) of disc storage, and requires 21 minutes of CPU time in the UNM IBM 360/67 computer. The range of subscripts for variables is specified by input data and may be any value within the above dimensioning with the exception of environmental receptors which are fixed within the code at four. Dimensioning may be increased if necessary, limited only by available core storage or other system requirements. Also, some exchanges of dimensioning can be used for special cases without increasing storage requirements. For example, 9 Release Model events, each with 4 component factors represent 36 storage combinations (= 9 x 4). If release is described by an involved function representing dynamic repository simulation (see Section 4.C.1.d), AMRAW can be dimensioned as one release event with up to 36 component factors if needed. The number of geographic zones, presently dimensioned at 8 is limited to 9 because of programming for the variable "NPRINT" which controls output options.

Large output matrices for local and nonspecific dose rates are written onto disc to conserve core space. Complete output is then written onto magnetic tape for retention but ouput may be diverted directly to printer by job control statements if preferred. Printed output is subsequently obtained from the tape as needed. If AMRAW-B is to be coupled to AMRAW-A for a combined run, AMRAW-B may access the disc for dose rate input data. The operation demonstrated at UNM is separate running of AMRAW-B. For this purpose, the dose rate portion of the AMRAW-A output is obtained from tape.

AMRAW-A has provisions for running more than one case, per submission. This can be: 1) more than one set of conditions for a waste management phase such as terminal storage, or 2) more than one phase, such as repository operations and terminal storage. A full set of input data is read in for each case.

There are three subroutines in AMRAW-A which evaluate transfer coefficients between sequential sections of the systems model (Fig. 4-2). Subroutine FAULT handles the Release Model (see Section 4.C.1) and provides the transfer coefficients used to accumulate releases to four preliminary input receptors from all release events considered. This subroutine uses function RLEACH when an event involves leaching into ground water. Subroutine TRINP handles transport from the preliminary input receptors to the environmental input receptors (see Section 4.D.1), providing transfer coefficients which account for physical and environmental decay and ground water transport delays. This subroutine uses function CRATIO for the ground water transport calculations. Use of the transfer coefficients from TRINP by the main program leads to net environmental concentrations for input to pathway analysis. Subroutine TRMAN handles evaluation of transfer coefficients between environmental concentrations and population dose rates (see Section 4.D.2) for the various pathways.

A directory of AMRAW-A output tables is given in Table 5-1. Output is divided into six sections, separated by divider pages. An output control parameter, NPRINT (see Vol. IV), controls which of the 10 types of tables are output and whether for all zones and organs or for only selected zones and/or organs. If all tables are output as currently implemented, 627 tables are obtained. If dimensioning for zones is increased from the present 8 to the program limit of 9, 68 additional tables could be generated. If in addition, Section 6 tables are requested for all 50 times, 810 more tables would result, for a possible total of 1505 tables. Clearly, discretion is called for when specifying requested output, particularly for the Section 6 group. In practice, an adequate sampling of Section 6 dose summary tables is obtained with 2 zones and 5 times, yielding only 20 tables from this section. In Table 5-1, the complete title for each type of table is stated, including the variable name called for and the units for the tabulated values. Each table as printed is identified with the appropriate radionuclide identification, zone number, and organ name as appropriate.

Table 5-1. Directory of AMRAW-A Output Tables

Description	[a]Number of Table Combinations				Total
	Nuclides	Zones	Organs	Environ. Receptors	
SECTION 1. Data Input					
1. Output listing of AMRAW input.	(20	pages)			
SECTION 2. Release to Environment					
1. Release Fractions by Each Cutset, RELOUT	25				25
2. Release Increments to Preliminary Environmental Input Receptors, R1J, from All Release Events, Ci	25			(4 in each table)	25
3. Concentrations at Environment Input Receptor, R2TOT. Units: JF = 1 μCi-y/cm^3, JF = 2 μCi/cm^2, JF = 3 and 4 μCi/cm^3.	25	8			200
SECTION 3. Local Dose to Individual					
1. Average Annual Local Dose to Individual, MAN1L, mren/y.	25	8	(8 in each table)		200
SECTION 4. Nonspecific Dose to Population					
1. Average Annual Nonspecific Dose to Population, MAN1N, manrem/y.	25		(8 in each table)		25

Table 5-1. Directory of AMRAW Output Tables (continued)

	Nuclides	Zones	Organs	Environ. Receptors	Total
SECTION 5. Total Dose by Receptors					
1. Average Annual Local Dose to Individual, MAN2LF for JF = 1 to 4, MAN2L for Total, mrem/y, Total for All Nuclides.		8	8	(4 in each table)	64
2. Average Annual Nonspecific Dose to Population, MAN2NF for JF = 1 to 4, MAN2N for Total, manrem/y, Total for All Nuclides.			8	(4 in each table)	8
SECTION 6. Dose Summary Tables					
1. Average Annual Local Dose to Individual, MAN1L, in Zone , mrem/y.	(25 in each table)	[b] up to 8	(8 in each table)	[c] 5	40
2. Average Annual Nonspecific Dose to Population, MAN1N, manrem/y.	(25 in each table)	[b] up to 8	(8 in each table)	[c] 5	40
Total Number of Tables					627

Note:

a. All output tables, except Section 6 are for 50 time steps, 0 to 10^6 years.

b. Individual zones may be specified.

c. Section 6 may call for a table for each of all times beginning with 100 y or skip some times; 5 tables result if call for every ninth time.

CHAPTER 6

APPLICATION OF MODEL

The computer code that implements the Radioactive Waste Management Systems Model is totally dependent upon externally generated input data. One function subprogram calculates nuclide-dependent leach rates as a function of leaching duration when called upon by the Release Model. Another function subprogram calculates the nuclide-dependent concentration ratios for points of usage versus the point of release as a function of ground water transport time intervals. Both of these subprograms depend upon input data for values of all parameters used. All other calculations in AMRAW are arithmetic operations which collect appropriate numerical components from the input data for the calculations, accumulate totals from contributing increments, and route results to the appropriate output tables. The nature of the input data dictates: 1) the waste management phase studied, 2) the inventory accumulation of radionuclides and their buildup and decay, 3) release scenarios, whether probabilistic, discrete events, statistical occurrence or dynamic repository simulation, 4) transport to environmental receptors via air dispersion to each geographic zone, ground water transport and by other transport mechanisms, 5) nuclide concentrations in food associated with depositions, 6) agricultural production and exposed populations, and 7) dose commitment rates associated with calculated intakes and exposures. The flexibility in AMRAW implementation permits use of various existing and accepted codes, reviewed and published data compilations, and estimates by experts in various fields, for preparation of input data.

Chapter 4 provides a step-by-step discussion of data needs in the generic sense. Volume II, Part 1, presents a base case which illustrates data acquisition for terminal storage at a specific repository site in bedded salt. Other cases illustrate sensitivity analysis showing the effects on calculated results of variations in selected input parameters, and consequence analysis showing consequences following discrete release events and the effect of the time of occurrence. Part 2 of Vol. II demonstrates other applications of the model. These include a case demonstrating preliminary application to the repository operations phase, discussion of application to ground surface storage, a case demonstrating a preliminary application to another geologic setting (repository in shale), and a discussion of model feasibility for application to other radioactive and nonradioactive hazardous materials.

Volume III describes the AMRAW-B part of AMRAW and demonstrates implementation for the base case dose rates obtained with AMRAW-A and for several consequence analysis cases. Volume IV is the AMRAW user's manual which provides specific information on input data formats and sequence. Part 1 of Vol. IV is for AMRAW-A and Part 2 is for AMRAW-B.

APPENDIX A

CONCENTRATION DISTRIBUTIONS IN GROUND WATER TRANSPORT

1. Line Source Equivalent of Plane Source. The solution of the radionuclide mass transfer equation (Eq. 4-79), from Duguid [ANS], for the instantaneous release from a rectangular plane source of width f, parallel to the y-z plane and centered at the origin is

$$C = \frac{M''}{4(\pi E_x t)^{\frac{1}{2}}} \exp - \left[\frac{(x - k_2 v_p t)^2}{k_3 v_p t}\right]\left[\operatorname{erf}\left(\frac{y + f/2}{2\sqrt{E_y t}}\right) - \operatorname{erf}\left(\frac{y - f/2}{2\sqrt{E_y t}}\right)\right] \tag{A-1}$$

where M" is the mass (or Curies used here) per unit area of the plane source, obtained by dividing the released quantity of a particular radionuclide by the product of the width f and the aquifer thickness z_a. Other parameters are as defined in Chapter 4.

It is now desired to obtain the equivalent solution for the instantaneous release from a line source located at the origin and parallel to the z-axis. The line source equation compresses the plane source into a width which approaches zero, providing for simpler calculations.

The form of the error function is

$$\operatorname{erf} u = \frac{2}{\sqrt{\pi}} \int_0^u e^{-\eta^2}\, d\eta \tag{A-2}$$

$$\operatorname{erf}' u = \frac{d}{du}(\operatorname{erf} u) = \frac{2}{\sqrt{\pi}} \frac{d}{du}\left(\int_0^u e^{-\eta^2}\, d\eta\right) = \frac{2}{\sqrt{\pi}} e^{-u^2} \tag{A-3}$$

Consider the error function factor in the exponent of Eq. A-1, and use Taylor's series to approximate the error functions. It is implicitly assumed that width f/2 becomes small when going to the line source, compared with distances y from the plume centerline.

$$\text{erf}\left(\frac{y + f/2}{2\sqrt{E_y t}}\right) - \text{erf}\left(\frac{y - f/2}{2\sqrt{E_y t}}\right) = \text{erf}\left(\frac{y}{2\sqrt{E_y t}}\right) + \frac{f}{4\sqrt{E_y t}}\ \text{erf}'\left(\frac{y}{2\sqrt{E_y t}}\right)$$

$$- \text{erf}\left(\frac{y}{2\sqrt{E_y t}}\right) + \frac{f}{4\sqrt{E_y t}}\ \text{erf}'\left(\frac{y}{2\sqrt{E_y t}}\right)$$

$$= \frac{f}{2\sqrt{E_y t}}\ \text{erf}\left(\frac{y}{2\sqrt{E_y t}}\right)$$

$$= \frac{f}{\sqrt{\pi E_y t}}\ \exp - \left(\frac{y}{2\sqrt{E_y t}}\right)^2 \qquad \text{(A-4)}$$

Substituting from Eq. A-4 into Eq. A-1, simplifying, and also substituting $M' = M'' f$ (release per unit of aquifer thickness), obtains

$$C = \frac{M'}{4\pi\sqrt{E_x E_y}\ t}\ \exp - \left[\frac{(x - k_2 v_p t)^2}{k_3 v_p t} + \frac{y^2}{4E_y t}\right] \qquad \text{(A-5)}$$

Using the following substitutions from Chapter 4:

$$k_1 = \frac{M'}{4\pi(a_L a_T)^{1/2}/R_d} \qquad k_3 = \frac{4a_L}{R_d}$$

$$k_2 = \frac{1}{R_d} \qquad k_4 = \frac{4a_T}{R_d}$$

$$E_x = \frac{1}{R_d} a_L v_p = \frac{1}{4} k_3 v_p$$

$$E_y = \frac{1}{R_d} a_T v_p = \frac{1}{4} k_4 v_p ,$$

Eq. A-5 becomes

$$C = \frac{k_1}{v_p t} \exp - \left[\frac{(x - k_2 v_p t)^2}{k_3 v_p t} + \frac{y^2}{k_4 v_p t} \right] \qquad \text{(A-6)}$$

which is Eq. 4-84 in Chapter 4 and is equivalent to an equation by Duguid [ANS] for the line source. As shown later, with input of an effective value of y (parameter YY), Eq. A-6 as calculated in AMRAW provides the average concentration within the equivalent plume width (parameter YW, the width within which $C > .001\ C_{max}$).

Figure A-1 shows computer generated plots of concentration versus y at a distance of x - 10 km for the plane source (f = 3000 m). Eq. A-1 and the line source Eq. A-6 for a 1 Ci instantaneous release in an aquifer of thickness z_a = 50 m. Other values of parameters used are from the application in Volume II: a_L = 50 m, a_T = 6 m, and v_p = 1.46 m/y. The plots shown represent the distributions at the time of peak passage at distance x; any consistent pair of time t and retardation factor R_d applies. The areas under the two curves are equal, indicating equivalency of the two source concepts.

Figure A-2 presents isometric views of 3-dimension computer plots of the concentration distributions in peaks at the time of arrival of the maximums at a distance of 10 km, for a plane source (length 3 km) and the equivalent line source. The computer plots are normalized to the same maximum ordinate value; actually, the line source peak is approximately 3.4 times as high as for the plane source (as in Fig. A-1) such that the volumes within the solid surfaces are equal. It should be noted that the leading face, as a peak approaches, is steeper than trailing force. The integrated volumes

$$\text{Volume} = z_a \int_0^{\infty}\int_0^{\infty} C(x,\ y)\ dy\ dx\ ,\quad \text{Ci}, \qquad \text{(A-7)}$$

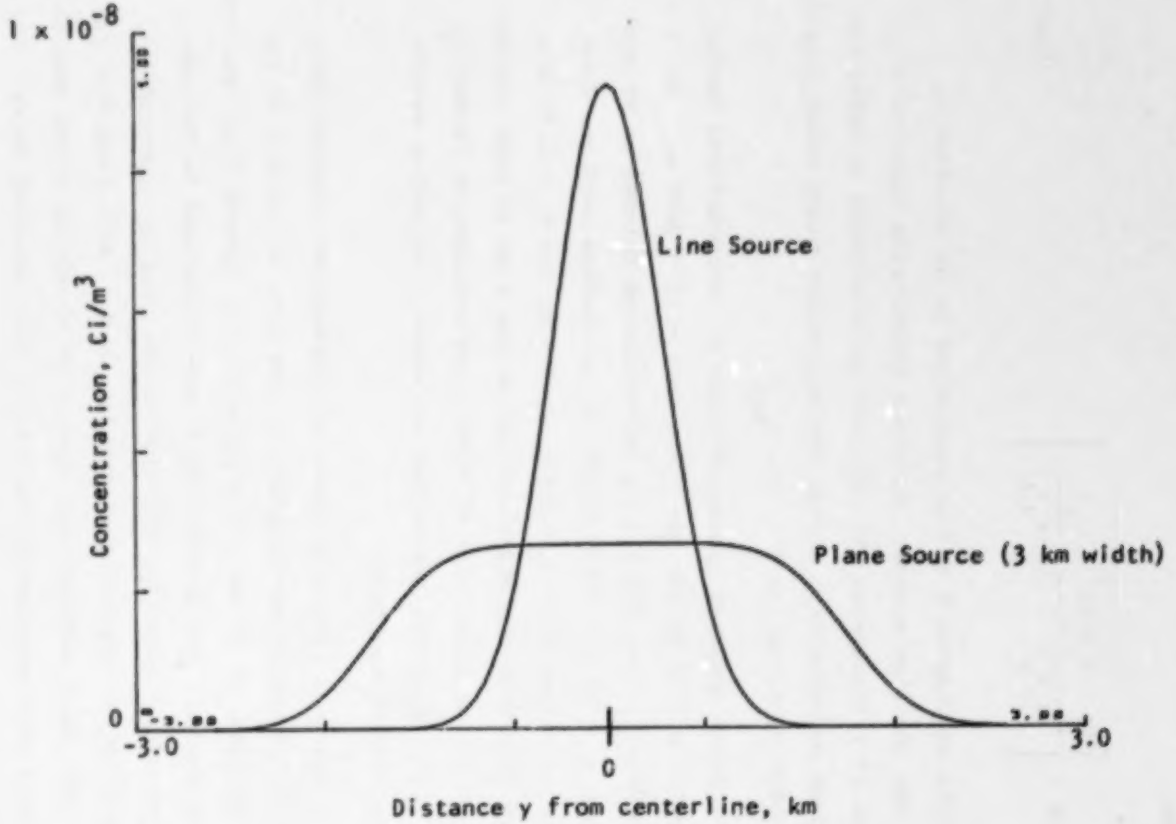
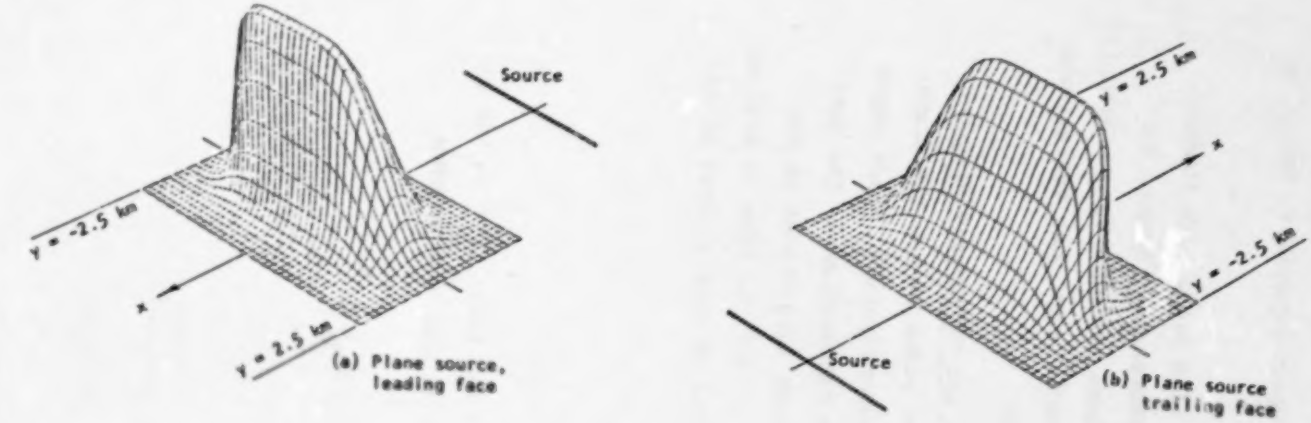
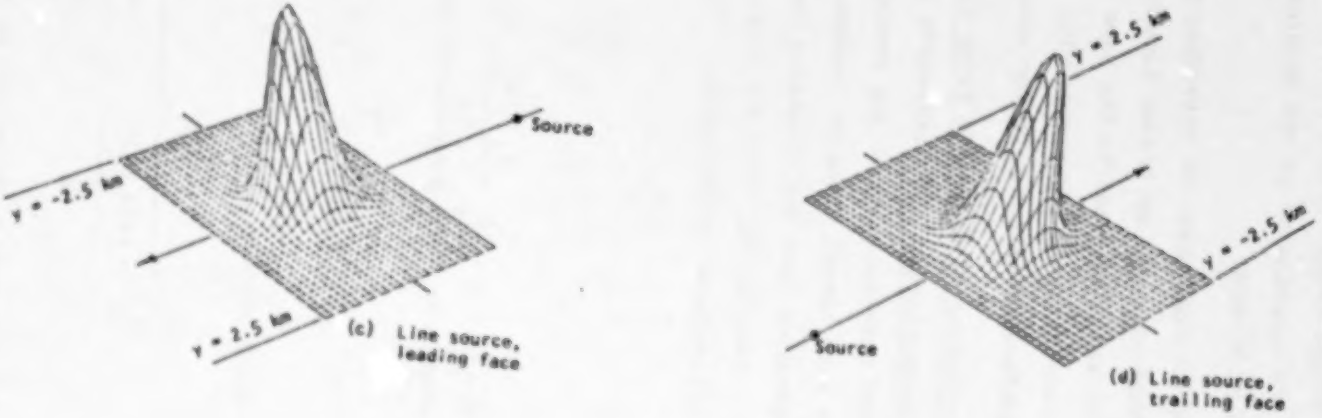


Figure A-1. Transverse distribution of concentration of peaks at distance of 10 km for plane and line sources.



(a) Plane source, leading face

(b) Plane source trailing face



(c) Line source, leading face

(d) Line source, trailing face

Figure A-2. Concentration distribution 10 km from the source for plane and line sources with instantaneous release.

calculated by computer show that an instantaneous release of 1 Ci is properly accounted for by Eqs. A-1 and A-6 for a plane source and a line source, respectively. This proving step has shown that porosity ε, contained in the denominator of the original Duguid equations, should be omitted as is done here.

Figure A-3 illustrates the spreading out of a peak, both longitudinally and transversely, as travel distance increases. Again, the computer plots are normalized to the same maximum ordinate value; actually, the maximum concentration decreases with distance such that the volumes within the surfaces (see Eq. A-7) are constant.

2. Calculation of Effective Plume Width and Transverse Distance to Average Concentration. The effective plume width YW and the transverse distance corresponding to the average concentration YY are input to AMRAW for each travel distance involved in calculations. The derivation of equations used for obtaining the input data values is presented here. Consider Eq. A-6, and simplify it for the time of arrival of the centerline peak concentration. The time of peak arrival at distance x is

$$t = \frac{xR_d}{v_p} .$$

Then $(x - k_2 v_p t) = x - \frac{1}{R_d} \cdot \frac{v_p\ x\ R_d}{v_p} = 0$, and the first term in the exponential drops out. The denominator of the second term becomes

$$k_4 v_p t = 4\ \frac{a_T}{R_d} \cdot v_p \cdot \frac{xR_d}{v_p} = 4a_T x .$$

The coefficient becomes

$$\frac{k_1}{v_p t} = \frac{M/z_a}{\dfrac{4\pi (a_L a_T)^{1/2}}{R_d} \cdot v_p \cdot \dfrac{xR_d}{v_p}} = \frac{M/z_a}{4\pi (a_L a_T)^{1/2} x}$$

Equation A-6 for peak distribution at x becomes

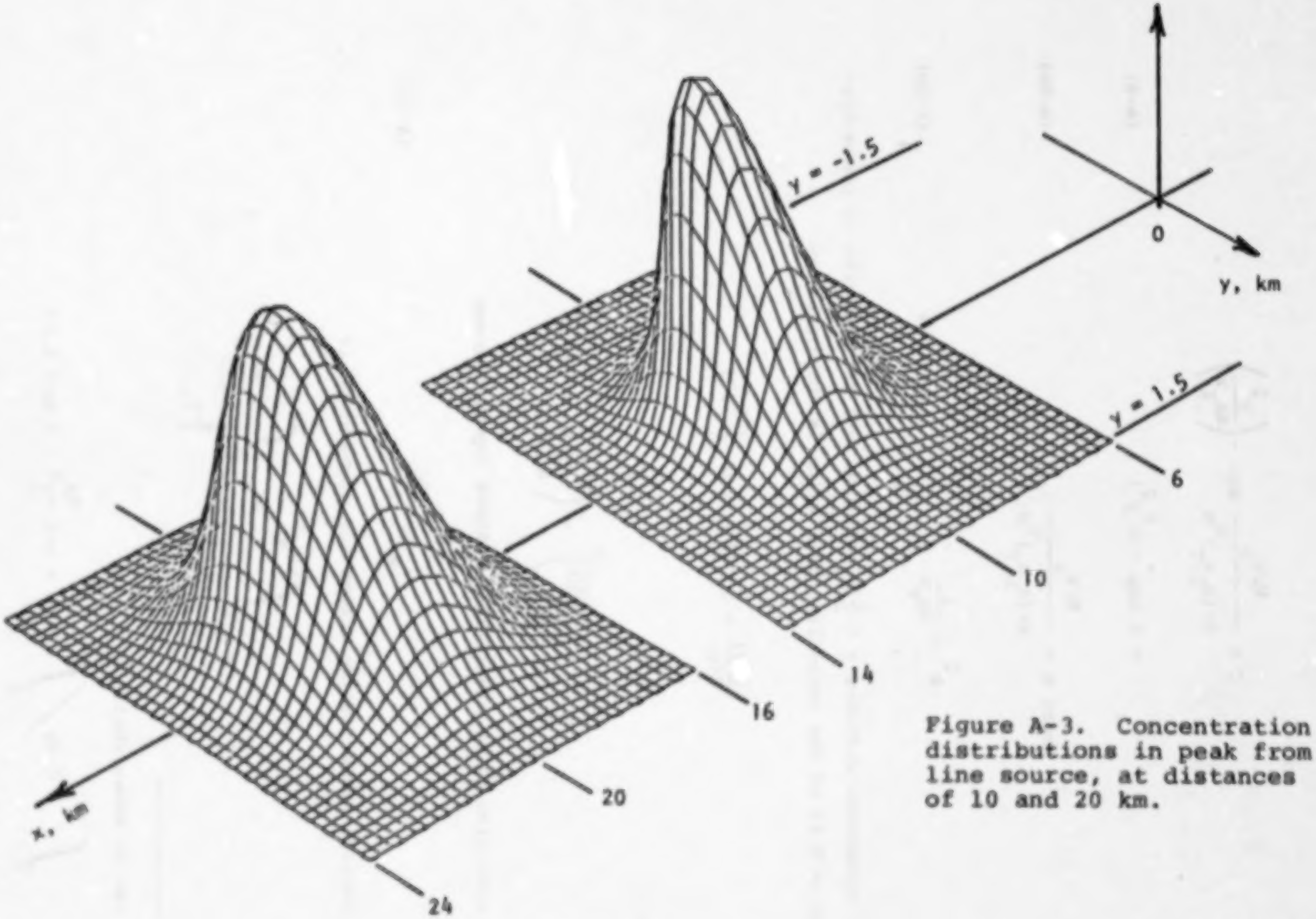


Figure A-3. Concentration distributions in peak from line source, at distances of 10 and 20 km.

$$C = \frac{M/z_a}{4\pi(a_L a_T)^{\frac{1}{2}} x} \exp -\left(\frac{y^2}{4a_T x}\right)$$

$$= A \exp -(B^2 y^2) \ . \qquad \text{(A-8)}$$

$$\text{where } A = \frac{M/z_a}{4\pi(a_L a_T)^{\frac{1}{2}} x} \qquad \text{(A-9a)}$$

$$B^2 = \frac{1}{4a_T x} \qquad \text{(A-9b)}$$

The transverse distance $y = \frac{1}{2} y_w$ (Figure A-4) for decrease in concentration to 0.1% of the centerline peak value is obtained from

$$\frac{C(y)}{C(o)} = 0.001 - \exp -\left(B^2 y^2\right)$$

Then,

$$y = \left(\frac{\ln 0.001}{-B^2}\right)^{\frac{1}{2}} = \left(\frac{6.91}{B^2}\right)^{\frac{1}{2}} = \frac{2.63}{B}$$

The effective plume width (YW for AMRAW input) becomes

$$y_w = \frac{5.26}{B} \qquad \text{(A-10)}$$

The average concentration across the plume width is

$$\overline{C} = \frac{\int_o^{\frac{1}{2} y_w} C \, dy}{\frac{1}{2} y_w} = \frac{\int_o^{\infty} C \, dy}{\frac{1}{2} y_w}^{a}$$

---

[a] It can be shown that

$$\int_o^{\frac{1}{2} y_w} C \, dy \bigg/ \int_o^{\infty} C \, dy = \text{erf} \frac{By_w}{2} = \text{erf } 2.63$$

and $0.3998 < \text{erf } 2.63 < 1.0000$. Therefore, the integrals are equal to 3 significant figures.

$$= \frac{A \int_0^{\infty} \exp - B^2 y^2 \, dy}{\frac{1}{2} y_w} = \frac{A\sqrt{\pi}}{2B\left(\frac{1}{2} y_w\right)} = \frac{A\sqrt{\pi}}{B y_w} \ . \qquad \text{(A-11)}$$

Substituting for B from Eq. A-10,

$$\overline{C} = \frac{A\sqrt{\pi}}{5.26} = 0.337 \ A \ . \qquad \text{(A-12)}$$

At what value of y does Eq. A-8 yield $\overline{C}$ directly? From A-8,

$$0.337 \ A = A \exp - (B^2 y^2)$$

$$y^2 = \frac{\ell n \ 0.337}{-B^2}$$

$$y = \frac{1.04}{B} \ . \qquad \text{(A-13)}$$

This is the traverse distance corresponding to the average concentration, input as YY to AMRAW.

To illustrate evaluation of AMRAW input parameters, again consider values of parameters from the application in Volume II: $a_T = 6$ m. For a travel distance of x = 10 km (10,000 m), from Eq. A-9b,

$$B = \frac{1}{2(a_T x)^{\frac{1}{2}}} = \frac{1}{2(60{,}000)^{\frac{1}{2}}} = 2.04 \times 10^{-3} \ m^{-1} \ .$$

Then, from Eq. A-10

$$YW = y_w = \frac{5.26}{B} = \frac{5.26}{2.04 \times 10^{-3}} = 2{,}580 \ m \ .$$

and from Eq. A-13,

$$YY = y_y = \frac{1.04}{B} = \frac{1.04}{2.04 \times 10^{-3}} = 510 \ m.$$

It may be noted that YW and YY depend only upon a_T and x; as such, AMRAW could calculate YW and YY but these values are included as input data (for x values appropriate to each zone) for greater flexibility.

In summary, substituting for B from Eq. A-9b, the effective plume width, from Eq. A-10, is

$$y_w = 10.5(a_T x)^{\frac{1}{2}} \tag{A-14}$$

and the transverse distance corresponding to the average concentration, from Eq. A-13, is

$$y_y = 2.08(a_T x)^{\frac{1}{2}} \ . \tag{A-15}$$

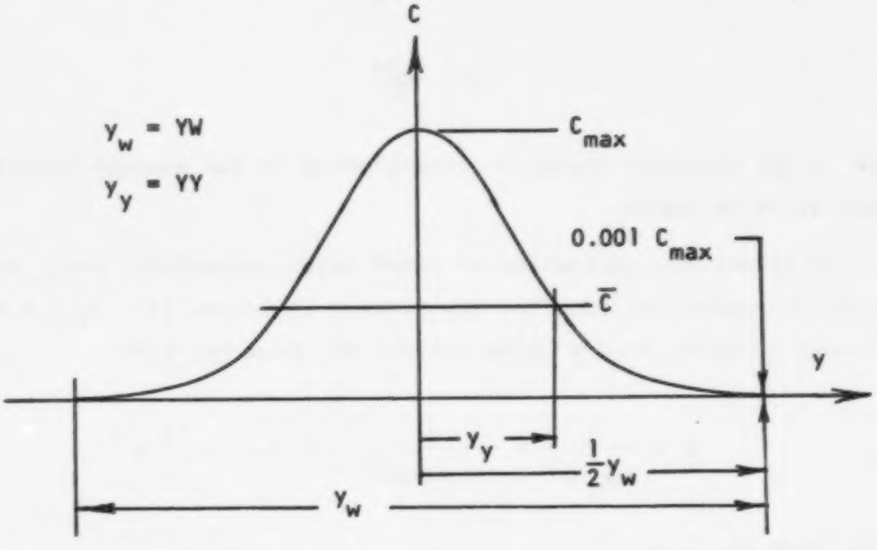


Figure A-4. Effective plume dimensions.

APPENDIX B

RADIONUCLIDE CONCENTRATIONS IN TERRESTRIAL FOODS

The transfer coefficient used in AMRAW for environment-to-man pathways (see Section 4.D.2) includes a component factor, BIOFAC, which relates radionuclide concentration in food to a unit concentration in a corresponding environmental input receptor. In AMRAW, the calculations for terrestrial (land surface receptor) pathways are based upon the concept of integrated food concentration following an acute deposition. There is a numerical equivalence between: 1) the ratio of the equilibrium concentration in food, μCi/g, to a unit continuous surface deposition rate, $\mu Ci/cm^2$-d, and 2) the ratio of the integrated concentration in the food, μCi-d/g, to a unit acute surface deposition, $\mu Ci/cm^2$.

A systems analysis methodology developed at the Oak Ridge National Laboratory by Booth et al. [Bh71] has a three-fold purpose of: 1) predicting intakes by man, 2) estimating dose commitments, and 3) identifying "critical" exposure pathways resulting from radioactivity releases to a terrestrial environment. An important part of this methodology is a generalized dynamic model simulating selected terrestrial pathways which assumes that fallout is the only source compartment and that man is the ultimate receptor compartment of interest. The model is implemented by the computer code TERMCD [Kℓ76]. A similar code, FOOD, was developed at Battelle Pacific Northwest Laboratory by Baker et al. [Ba76].

Discussion is presented here to support the observation that integration of concentrations in terrestrial foods versus time is virtually complete within a period of five years after an acute deposition.

1. Introduction. The mathematical compartment models depicting terrestrial pathways, as developed by Booth and co-workers [Bh71] is shown in Fig. B-1. The objective of this model is to obtain predictions of radionuclide intakes by man through consumption of milk, beef, and plant parts contaminated as a result of fallout. Fig. B-1 indicates a fallout rate, $\mu Ci/m^2$-d, but it is shown later that the system equations may also be solved for an initial one-time deposition, in units of $\mu Ci/m^2$.

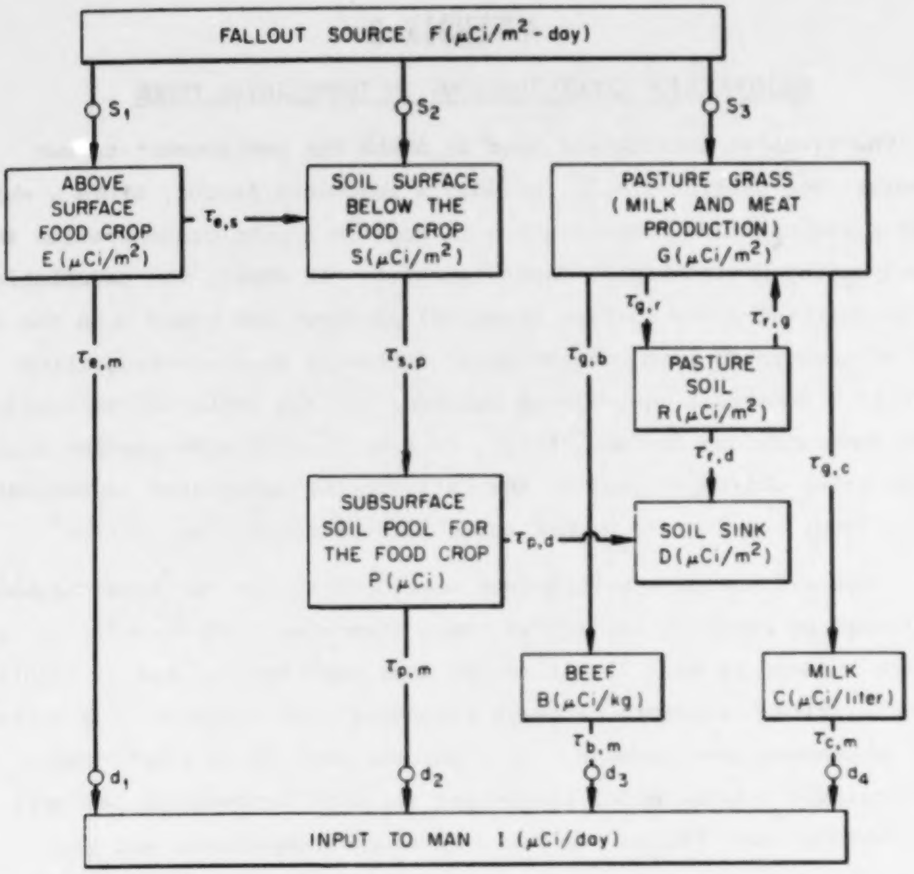

FALLOUT SOURCE F(μCi/m² - day)
S1
S2
S3
ABOVE SURFACE FOOD CROP E(μCi/m²)
τe,s
SOIL SURFACE BELOW THE FOOD CROP S(μCi/m²)
PASTURE GRASS (MILK AND MEAT PRODUCTION) G(μCi/m²)
τg,r
τr,g
τe,m
τs,p
τg,b
PASTURE SOIL R(μCi/m²)
τr,d
τg,c
SUBSURFACE SOIL POOL FOR THE FOOD CROP P(μCi)
τp,d
SOIL SINK D(μCi/m²)
τp,m
BEEF B(μCi/kg)
MILK C(μCi/liter)
τb,m
τc,m
d1
d2
d3
d4
INPUT TO MAN I (μCi/day)

Figure B-1. Compartment diagram of the terrestrial food pathways by which radioactivity can be transferred to man [Bh71].

Considering the above-surface food crop (ASF) first, a fraction S_1 of the fallout deposits on the food and a fraction S_2 (where $S_1 + S_2 = 1.0$) deposits on the soil surface below the food crop. The radioactivity enters the ASF crop by deposition and is retained either by external adhesion to, or foliar absorption into, the crop's edible parts. This crop is assumed to be continuously harvested during and after fallout, with biomass removal balanced by crop growth. Transfer rate coefficients, τ, are shown between the various compartments in Fig. B-1. Washoff from ASF to the soil surface below is represented by $\tau_{e,s}$. The half-time for this is generally taken as 14 days (taken as 30 days for desert grazing land in Vol. II), corresponding to $\tau_{e,s} = 0.693/14 = 0.05 \cdot d^{-1}$. The other removal of ASF radioactivity is by harvesting the crops, represented by $\tau_{e,m}$, and transfer directly to man. Contamination on the soil surface moves down into the subsurface soil pool (root zone) at the rate $\tau_{s,p}$, and from there, moves below the root zone into the soil sink at the rate $\tau_{p,d}$. This model does not consider root uptake by ASF but simulates this instead by the link $\tau_{p,m}$ between the soil pool and man. Root uptake can be shown to represent at most only a few percent of ASF concentrations.

Next, consider meat and milk production. A fraction S_3 of the fallout deposits on pasture grass (or rangeland vegetation as appropriate). Washoff to pasture soil surface is per $\tau_{g,r}$ and root uptake in per $\tau_{r,g}$. Again radionuclides in the pasture soil migrate to the soil sink at rate $\tau_{r,d}$. Meanwhile, transfer to meat and milk via consumption of pasture grass is by $\tau_{g,b}$ for meat (beef) and $\tau_{g,c}$ for milk. The transfer rates from meat and milk to man are $\tau_{b,m}$ and $\tau_{c,m}$, respectively. The milk compartment variable C(t) is the concentration of radioactivity in milk produced by a cow grazing on the contaminated pasture. In the Booth model, radioactivity is transferred from the grass directly to the milk; this simulation is used mainly because the milk of grazing cows can be in transient equilibrium with the forage radioactivity after about two days. The beef compartment variable B(t) is the radioactivity in the meat or muscle of cattle grazing on the contaminated pasture. Radioactivity is directly transferred from the grass to the meat as in the milk compartment; removal is via radiodecay, biological elimination, and slaughter of the cattle. Transfer to uncontaminated feed lots terminates intake of radionuclides. The parameters d_1 through d_4 in Fig. B-1 are dietary correction factors which account for cleaning and trimming of food. The gradual accumulation in the soil sink effectively removes radionuclides from food pathways and limits the duration of impact following deposition.

AMRAW applies this model only for determining the concentrations in ASF, meat and milk, in relation to deposition. Intake rates of these foods and corresponding dose commitment rates are handled in AMRAW.

2. Formulation of the System Equations. Referring to Fig. B-1, the conservation equation describing the rate of change of contamination of above-surface food crops, E(μCi/m^2), [Bh71] is

$$\frac{dE}{dt} = S_1 F(t) - \lambda_a E \qquad \text{(B-1)}$$

where $F(t)$ = deposition as function of time,

$\lambda_a = \lambda_R + \frac{\tau_{e,m}}{A} + \tau_{e,s}$, effective removal constant, d^{-1},

λ_R = radiodecay constant, d^{-1},

$\tau_{e,m}$ = crop harvest rate, m^2/d,

A = soil surface area producing food crops for one person, $10^3 m^2$, and

$\tau_{e,s}$ = fractional transfer rate, foliage to soil surface, d^{-1}.

Other parameters have been discussed previously. It should be noted here that this model expresses ASF contamination in terms of crop area; application in AMRAW requires conversion to μCi/g (typically using 100 g/m^2 for the conversion). The equation for soil surface below the food crop, $S(\mu Ci/m^2)$ is

$$\frac{dS}{dt} = \tau_{e,s} E - \lambda_s S + S_2 F(t), \ \mu Ci/m^2 \qquad \text{(B-2)}$$

where $\lambda_s = \lambda_R + \tau_{s,p}$, effective removal constant, d^{-1},

$\tau_{s,p}$ = fractional transfer rate, soil surface to soil pool, d^{-1}, and

$\tau_{e,s}$ = fractional transfer rate, crops to soil surface, d^{-1}.

Subsurface soil pool concentration, P, is μCi associated with one person's food supply, typically 1000 m^2. This changes as

$$\frac{dP}{dt} = A\tau_{s,p} S - \lambda_p P \qquad \text{(B-3)}$$

where $\lambda_p = \lambda_R + \tau_{p,m} + \tau_{p,d}$, effective removal constant, d^{-1},

$\tau_{p,m}$ = fractional transfer rate, soil pool to man, d^{-1},

$\tau_{p,d}$ = fractional transfer rate, soil pool to soil sink, d^{-1}, and

$\tau_{s,p}$ = fractional transfer rate, soil surface to soil pool, d^{-1}.

Moving to the pasture pathways, pasture grass contamination, G, $\mu Ci/m^2$, responds as

$$\frac{dG}{dt} = S_3F(t) - \lambda_g G + \tau_{r,g} R \qquad \text{(B-4)}$$

where $\lambda_g = \lambda_R + \tau_{g,r} + V_c/A_gD_g$, effective removal constant, d^{-1},

$\tau_{g,r}$ = fractional transfer rate, grass to soil, d^{-1},

V_c/A_gD_g = fractional grass consumption rate, d^{-1} (related to $\tau_{g,b}$ and $\tau_{g,c}$, Fig. B-1), and

$\tau_{r,g}$ = fractional root uptake rate, soil to grass, d^{-1}.

Pasture soil contamination, R, $\mu Ci/m^2$, changes as

$$\frac{dR}{dt} = \tau_{g,r} G - \lambda_r R \qquad \text{(B-5)}$$

where $\lambda_r = \lambda_R + \tau_{r,g} + \tau_{r,d}$, effective removal constant, d^{-1}, and

$\tau_{r,d}$ = fractional transfer rate, pasture soil to soil sink, d^{-1}.

Soil sink lumps sinks for crops and pasture areas in D, $\mu Ci/m^2$ as

$$\frac{dD}{dt} = \tau_{r,d} R + \frac{\tau_{p,d}}{A} P - \lambda_R D.$$

Contamination in milk, C, $\mu Ci/\ell$, varies as

$$\frac{dC}{dt} = \tau_{g,c} G - \lambda_c C \qquad \text{(B-6)}$$

where $\lambda_c = \lambda_R + \tau_{milk}$, effective removal constant, d^{-1},

τ_{milk} = transfer rate from udder, d^{-1}, and

$\tau_{g,c}$ = transfer rate, grass to milk, m^2/ℓ-d.

Contamination in beef, B, $\mu Ci/Kg$ varies as

$$\frac{dB}{dt} = \tau_{g,b} G - \lambda_b B \qquad \text{(B-7)}$$

where $\lambda_b = \lambda_R + \tau_{beef}$, effective removal constant, d^{-1},

τ_{beef} = fractional rate of removal of beef herd, d^{-1}, and

$\tau_{g,b}$ = transfer rate, grass to meat, m^2/kg-d.

All the above equations represent the change with time of the radioactivity in each compartment. Subsequent expressions for intake to man are omitted here; AMRAW provides this step.

3. Equilibrium Solutions for Constant Deposition Rate. If the deposition source, F(t), is set equal to a constant value, F, μCi/m^2-d, and the rates of change of compartment values are set equal to zero (e.g. dE/dt = 0), the equilibrium values are obtained:

$$E = S_1 F/\lambda_a \tag{B-8}$$

$$S = (S_2 F + \tau_{e,s} E)/\lambda_s \tag{B-9}$$

$$P = A\tau_{s,p} S/\lambda_p \tag{B-10}$$

$$G = (S_3 F + \tau_{r,g} R)/\lambda_g \tag{B-11}$$

$$R = \tau_{g,r} G/\lambda_p \tag{B-12}$$

$$D = (\tau_{r,d} R + \tau_{p,d} P/A)/\lambda_R \tag{B-13}$$

$$C = \tau_{g,c} G/\lambda_c \tag{B-14}$$

$$B = \tau_{g,b} G/\lambda_b . \tag{B-15}$$

4. Transient Solutions for Unit Initial Deposition. The substitution $F(t) = F_o\ \delta(t)$, where $\delta(t)$ is the Kronecker delta function, represents a pulse or acute deposition, may be applied immediately before t = 0 such that $F(o) = F_o$. Then, the solution of Eq. B-1 is [Kr67]

$$E(t) = S_1 F_o e^{-\lambda_a t} . \tag{B-16}$$

For the soil surface below the food, the solution of Eq. B-2 is, noting that $S = S_2F_o$ at $t = 0$,

$$S(t) = \frac{S_1F_o\tau_{e,s}}{\lambda_s - \lambda_a}\left(e^{-\lambda_a t} - e^{-\lambda_s t}\right) + S_2F_oe^{-\lambda_s t}. \qquad \text{(B-17)}$$

The initial condition for the subsurface soil pool is $P = 0$ at $t = 0$. Then, using Eq. B-3, the solution of Eq. B-17 is [Kr67]

$$P(t) = -\frac{S_1F_o\tau_{e,s}\tau_{s,p}A}{(\lambda_s-\lambda_p)(\lambda_a-\lambda_s)(\lambda_p-\lambda_a)} \times$$

$$\left[(\lambda_a-\lambda_s)e^{-\lambda_p t} + (\lambda_p-\lambda_a)e^{-\lambda_s t} + (\lambda_s-\lambda_p)e^{-\lambda_a t}\right] + \frac{S_2F_o\tau_{s,p}A}{\lambda_s - \lambda_p}\left[e^{-\lambda_p t} - e^{-\lambda_s t}\right]. \qquad \text{(B-18)}$$

Subsequent solutions of B(t), C(t) and G(t) yield [Kr67]

$$B(t) = \frac{S_3F_o\tau_{g,b}}{(\lambda_b-\lambda_1)(\lambda_1-\lambda_2)(\lambda_2-\lambda_b)} \times$$

$$\left[(\lambda_b-\lambda_r)(\lambda_1-\lambda_2)e^{-\lambda_b t} + (\lambda_1-\lambda_r)(\lambda_2-\lambda_b)e^{-\lambda_1 t} + (\lambda_2-\lambda_r)(\lambda_b-\lambda_1)e^{-\lambda_2 t}\right] \qquad \text{(B-19)}$$

where $$\lambda_1 = \frac{\lambda_g + \lambda_r + \left[(\lambda_g+\lambda_r)^2 - 4(\lambda_g\lambda_r-\tau_{r,g}\tau_{g,r})\right]^{1/2}}{2}, \qquad \text{(B-20)}$$

$$\lambda_2 = \frac{\lambda_g + \lambda_r - \left[(\lambda_g+\lambda_r)^2 - 4(\lambda_g\lambda_r-\tau_{r,g}\tau_{g,r})\right]^{1/2}}{2}, \qquad \text{(B-21)}$$

$$C(t) = S_3F_o\tau_{g,c}\left[\frac{(\lambda_c-\lambda_r)(\lambda_1-\lambda_2)e^{-\lambda_c t} + (\lambda_1-\lambda_r)(\lambda_1-\lambda_c)e^{-\lambda_1 t}}{(\lambda_c-\lambda_1)(\lambda_1-\lambda_2)(\lambda_2-\lambda_c)}\right.$$

$$\left. + \frac{(\lambda_2-\lambda_r)(\lambda_c-\lambda_1)e^{-\lambda_2 t}}{(\lambda_c-\lambda_1)(\lambda_1-\lambda_2)(\lambda_2-\lambda_c)}\right], \qquad \text{(B-22)}$$

and

$$G(t) = S_3F_o\left[\frac{(\lambda_c-\lambda_2)(\lambda_2-\lambda_r)(\lambda_c-\lambda_1)e^{-\lambda_2 t}}{(\lambda_c-\lambda_1)(\lambda_1-\lambda_2)(\lambda_2-\lambda_c)} + \frac{(\lambda_c-\lambda_1)(\lambda_1-\lambda_r)(\lambda_2-\lambda_c)e^{-\lambda_1 t}}{(\lambda_c-\lambda_1)(\lambda_1-\lambda_2)(\lambda_2-\lambda_c)}\right] \qquad \text{(B-23)}$$

where λ_1 and λ_2 are defined in Eqs. B-20 and B-21, respectively. As noted earlier, the term A in Eq. B-18 is the soil surface area required to furnish food crops for one man (taken as 1000 m^2).

As an example, consider I-129. The long half-life for this isotope (1.7×10^7 y) illustrates the dominance of the other transfer coefficients over the physical decay constant. Subsituting values for parameters used by Booth et al. [Bo71, Kℓ76] for average U. S. conditions into Eq. B-16 B-19 and B-22 obtains the following food response equations, respectively, following deposition of F = 1 µCi/m^2.

$$E(t) = 0.1\ e^{-(5.2 \times 10^{-2})t} \tag{B-24}$$

$$B(t) = 2.30\ \Big[(2.06 \times 10^{-4})e^{-(3.81 \times 10^{-3})t} - (2.08 \times 10^{-4})e^{-(5.62 \times 10^{-2})t} + (1.42 \times 10^{-6})e^{-(1.10 \times 10^{-4})t}\Big] \tag{B-25}$$

$$C(t) = -\Big[0.306\quad 0.112\ e^{-2t} - 0.112\ e^{-(5.62 \times 10^{-2})t} - 5.25 \times 10^{-5}\ e^{-(1.10 \times 10^{-4})t}\Big]. \tag{B-26}$$

These are plotted in Fig. B-2, along with the corresponding curves for soil surface, subsurface pool, and pasture grass. The above-surface food concentration is a maximum initially and decays primarily by washoff. Milk concentration quickly builds up to a maximum at 3 days and meat reaches a maximum at approximately 80 days. The curves in Fig. B-2 have differing scale factors. To place the peaks in perspective, Table B-1 summarizes the peak values in the units determined by the compartment model, and converted to common units of µCi/g.

Table B-1. Peak Concentrations in Foods
Following Unit Deposition of I-129

		µCi/g
Above-Surface Food	0.1 µCi/m^2	1×10^{-3}
Milk	3×10^{-2} µCi/ℓ	3×10^{-5}
Meat	4×10^{-4} µCi/kg	4×10^{-7}

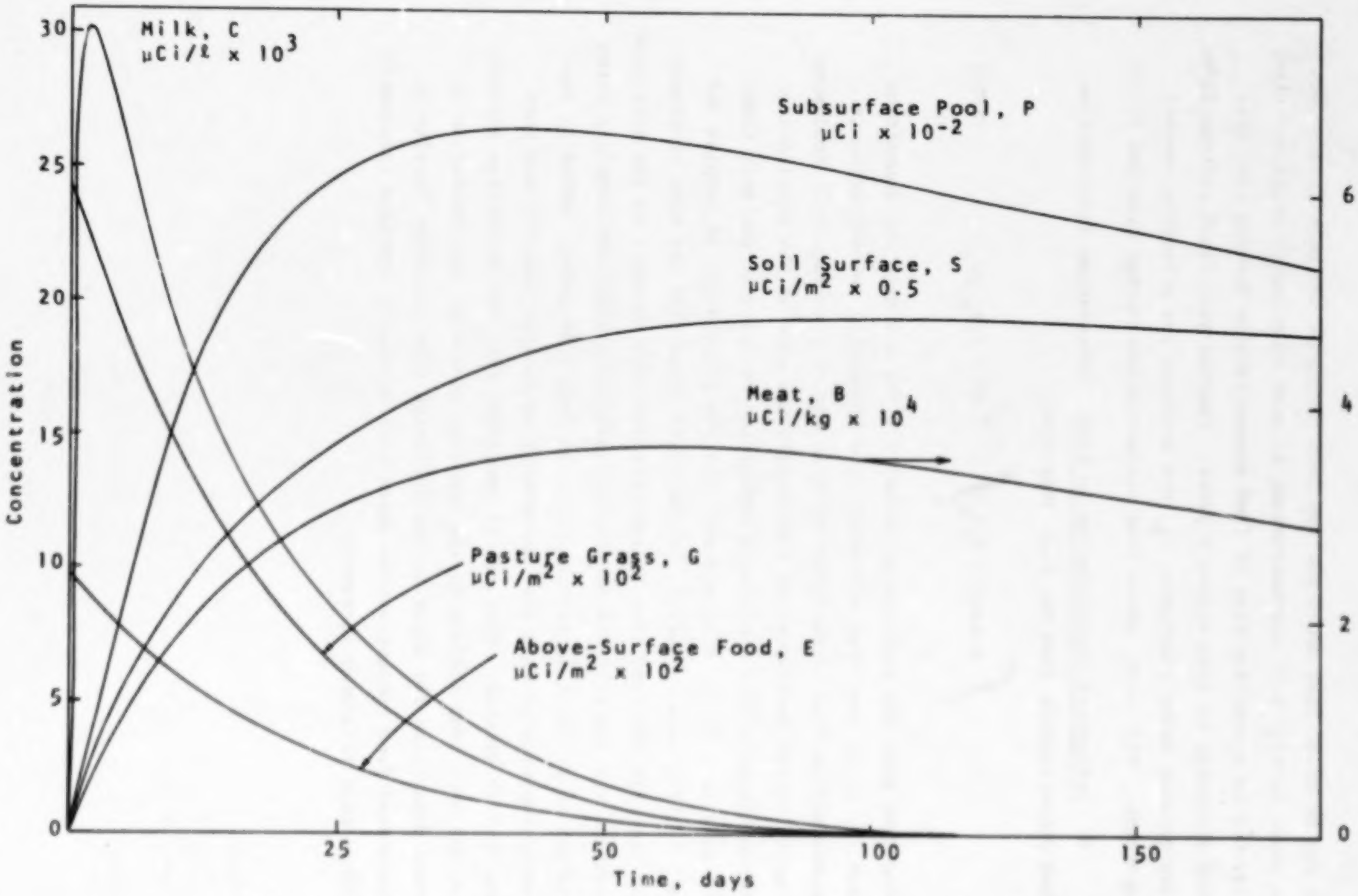


Figure B-2. Linear plot of I-129 concentrations in response to unit initial deposition of 1 $\mu Ci/m^2$.

It may be noted that above-surface food dominates the peak values, but as shown in Fig. B-2, concentrations in meat have longer residence times. Fig. B-3 is a semi-log plot of food concentrations showing that they drop virtually to zero within 5 years. Shorter half-lived radionuclides have greater decay constants, λ_R, and increase the effective removal constants. Fig. 4-16 shows food concentrations versus time for Sr-90.

5. Integrated Concentration in Food. Integrating above-surface food concentration from Eq. B-16 over time,

$$\int_0^\infty E(t)dt = S_1F_o\int_0^\infty e^{-\lambda_a t}dt = S_1F_o/\lambda_a. \qquad \text{(B-27)}$$

Comparing with the equilibrium value of E for a continuous deposition rate, F, it is seen that the total time integrated concentration in above-surface food (area under curve in Fig. B-2 or Fig. B-3) following a unit initial deposition is numerically the same as the equilibrium concentration with a continuous deposition of one unit per unit time. The same is true for milk and meat but the integration is complex and is not given here. Overall, the analysis shows that the time constants for transfer downward from foliage through soil horizons to the soil sink dominate the significance of physical half-life such that complete integration is practically attained in less than five years. AMRAW is currently implemented with time increments no shorter than 5 y and most are 10 y or greater. Thus, it is concluded that the deposition accumulations onto land surface during one time increment and treated as an acute deposition for input to the following time increment results in integrated food concentrations which have virtually complete integration within that following increment.

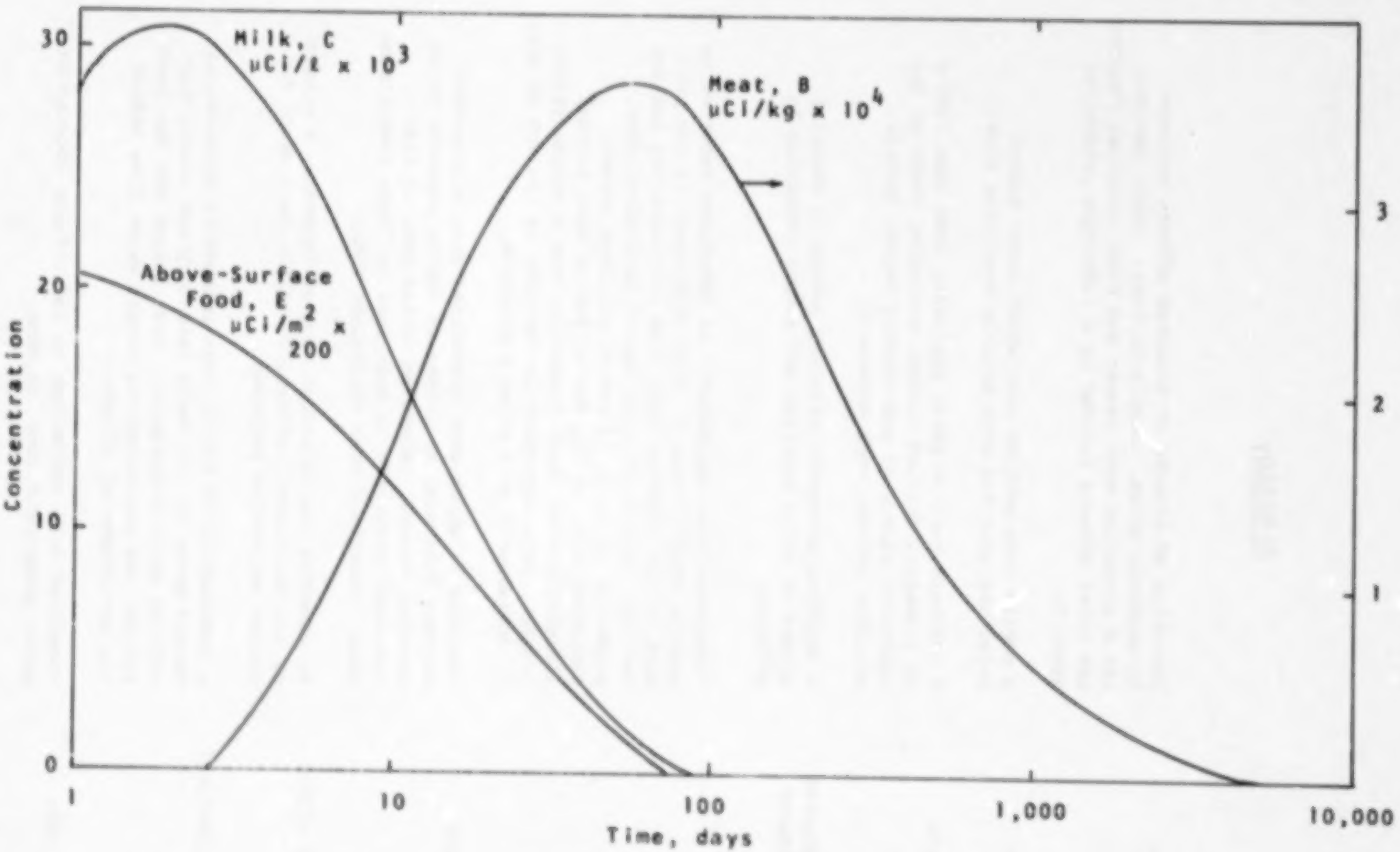


Figure B-3. Response of concentration of I-129 in food to unit initial deposition of 1 μCi/m^2.

GLOSSARY

damages	the value of adverse or unwanted effects measured in economic units, usually dollars. Total damages are a summation over causes and time; marginal damages are total damages divided by a reference production quantity.
diapir	a mobile core such as salt which moves upward injecting into the more brittle overlying rock.
diatreme	a volcanic vent or pipe, typically less than 1000 m in diameter, drilled through enclosing rocks by the explosive energy of gas-charged magmas (mobile, possibly molten, rock material).
distribution coefficient (K_d)	a sorption parameter relating amount of material sorbed on solid material and amount remaining in solution.
dose	"committed dose equivalent" is sometimes referred to here as simply "dose." Dose equivalent is the product of the absorbed dose from radioactivity and the quality factor, loosely called biological dose, expressed in units of rem or millirem (mrem). Committed dose is the sum of future dose accrual (generally over 50 y) resulting from a radioactivity intake. Dose expressed in man-rems is the sum of dose to individuals in a given population.
dose rate	the rate at which dose (committed dose equivalent) accrues following an intake or during exposure to an external source. Where an intake rate is also involved, reference is made here to "dose committment rate" (committed dose equivalent rate).
health effect	an unwanted health effect such as leukemia, a cancer, or serious genetic effect, equatable to a death for damage estimation purposes.
leach incident	a combination of events that introduces circulating ground water to the waste inventory and starts dissolving waste components. Time delays for the leach process and migration via ground water flow retard the environmental effects.
local dose	committed dose equivalent to individuals located in a given geographic zone, in mrem.

nonspecific dose	committed dose equivalent to an undefined population from consumption of largely exported agricultural products, in man-rem.
nuclide	a nuclear species characterized by the number of neutrons and protons in the nucleus. Used here at times in lieu of the more descriptive term: radionuclide.
offset faulting	movement producing relative displacement of adjacent rock masses along a fracture and resulting in a separation or gap.
probabilistic	based on probability, which is the number of times something will probably occur in a given amount of time. The probabilistic mode refers to operations with probabilities included in the calculations.
radionuclide	a nuclide which is unstable or radioactive.
release	a breach of containment which allows radioactive material to migrate through the geosphere. A release may or may not be directly to the biosphere.
resuspension	the process of material deposited onto land surface being picked up by wind action and resuspended.
risk	The product of probability of occurrence of an event and the consequences of an occurrence. As used in economics, risk refers to the chance of damage or loss.
sorption	an overall term referring to retention of a species on a solid by any of several processes such as absorption, adsorption, and ion exchange.
volcanic, volcanism	adjective and noun, respectively, pertaining to natural processes resulting in the formation of volcanoes or lava flows.
volcanic explosion	a violent explosive form of volcano ejecting material into the atmosphere.
volcanogenic transport	non-explosive carrying of material by any of three mechanisms: magma transport, volatile transport, or hydrothermal transport.

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